Exclusive 1 μ+Np Topologies in ArgoNeuT

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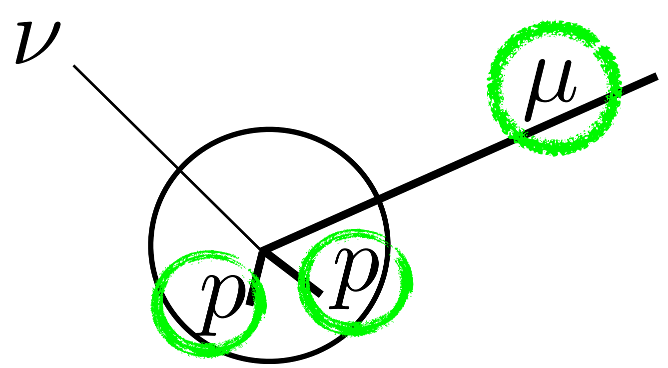
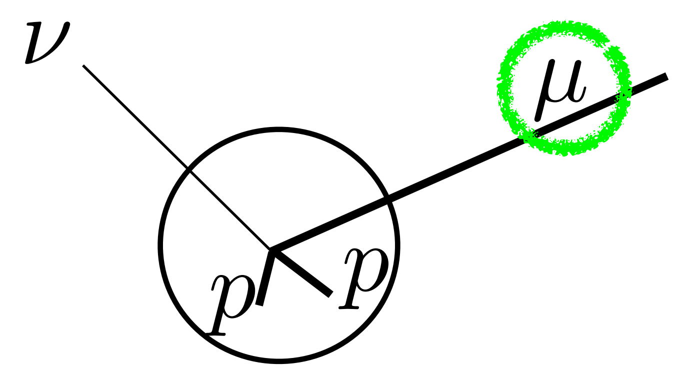
Philosophy



• initial state σ's
(corrected back to initial state)



• final state σ's
(do not correct out FSI)

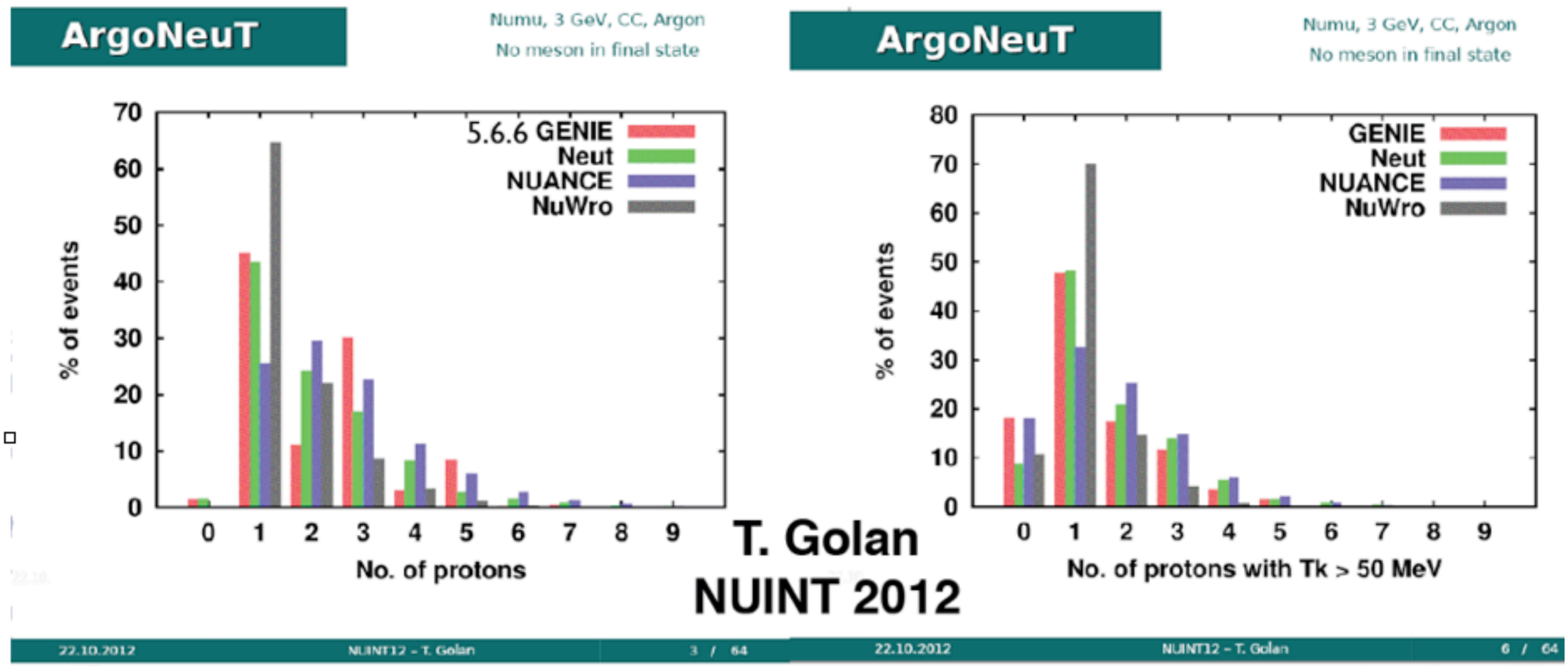
LAr

don't have to be restricted to measuring "QE", "CCπ^+", ... cross sections

Instead: Topological Analysis

- 1μ+Np where N=0,1,2...
- $1\mu+\pi$+Np
- etc.

Neutrino channel definitions are largely ill defined given the effects of FSI
We want to report what our detector actually sees!



- Accurate and extremely detailed MonteCarlo generators are needed for comparison with LAr data
- MonteCarlo Generators: FSI models for Ar need to be cross-checked by comparison of different MC generators
- FSI in MC codes represent the most difficult present challenge in MC development

How is the analysis done?

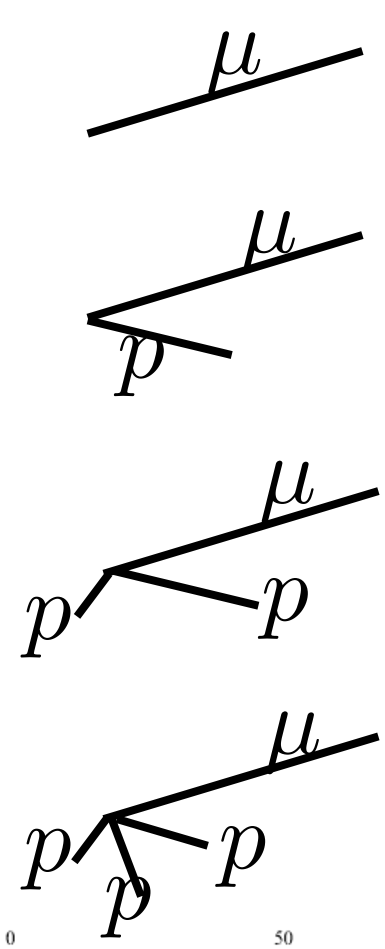
- Automatic reconstruction+visual scanning
  - Particle Identification
  - Proton threshold
  - Matching with MINOS Near Detector
  - final scanned sample includes events with contained protons in fiducial volume

- Efficiency and Purity for different proton multiplicities evaluated using a full MC simulation (GENIE/Geant4/Larsoft)
  - take proton containment into account
- Energy reconstruction with muon kinematics.

(Analysis including proton kinematics in progress, preliminary results will be shown)

$$E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos\theta_\mu)}$$

Topology appearance

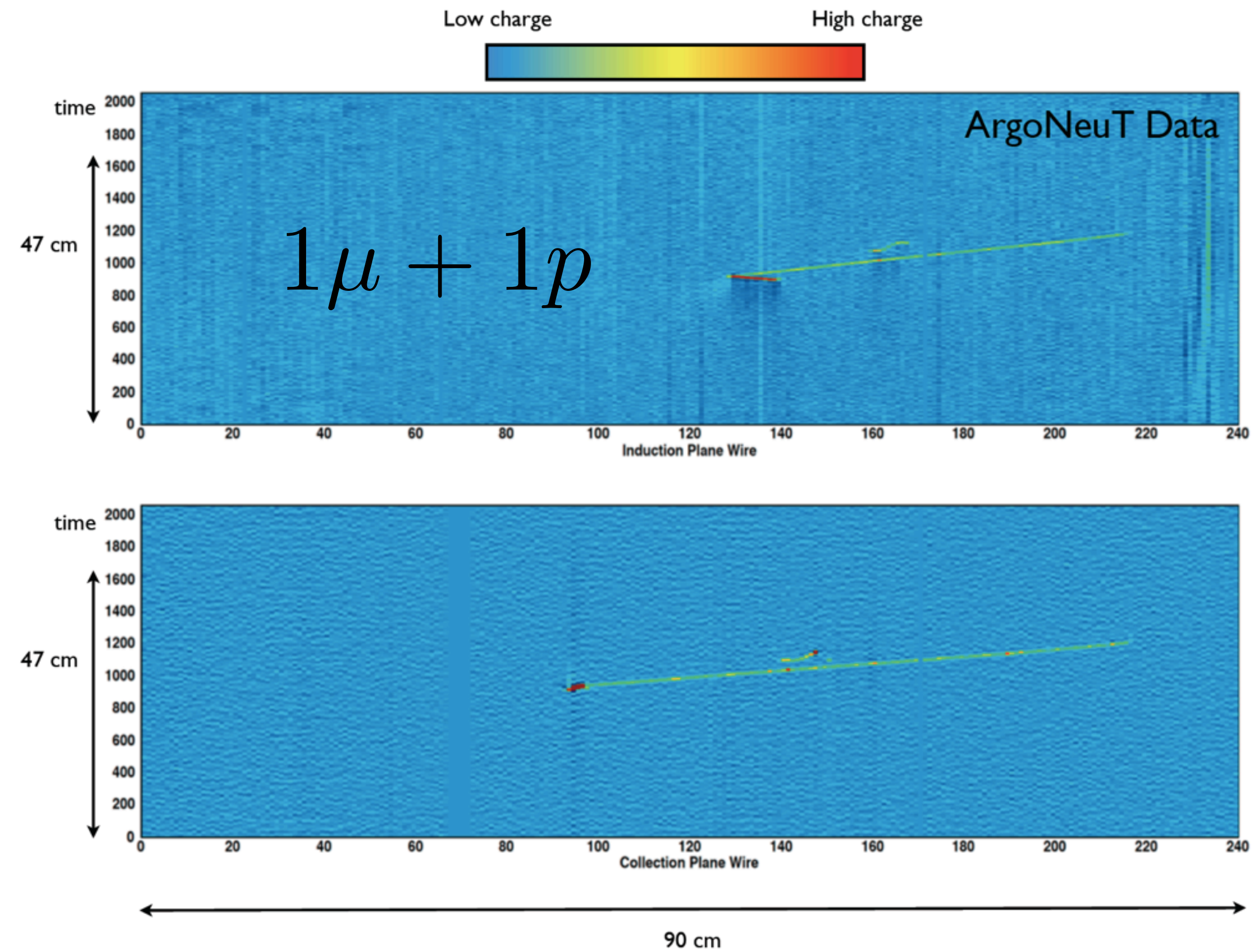


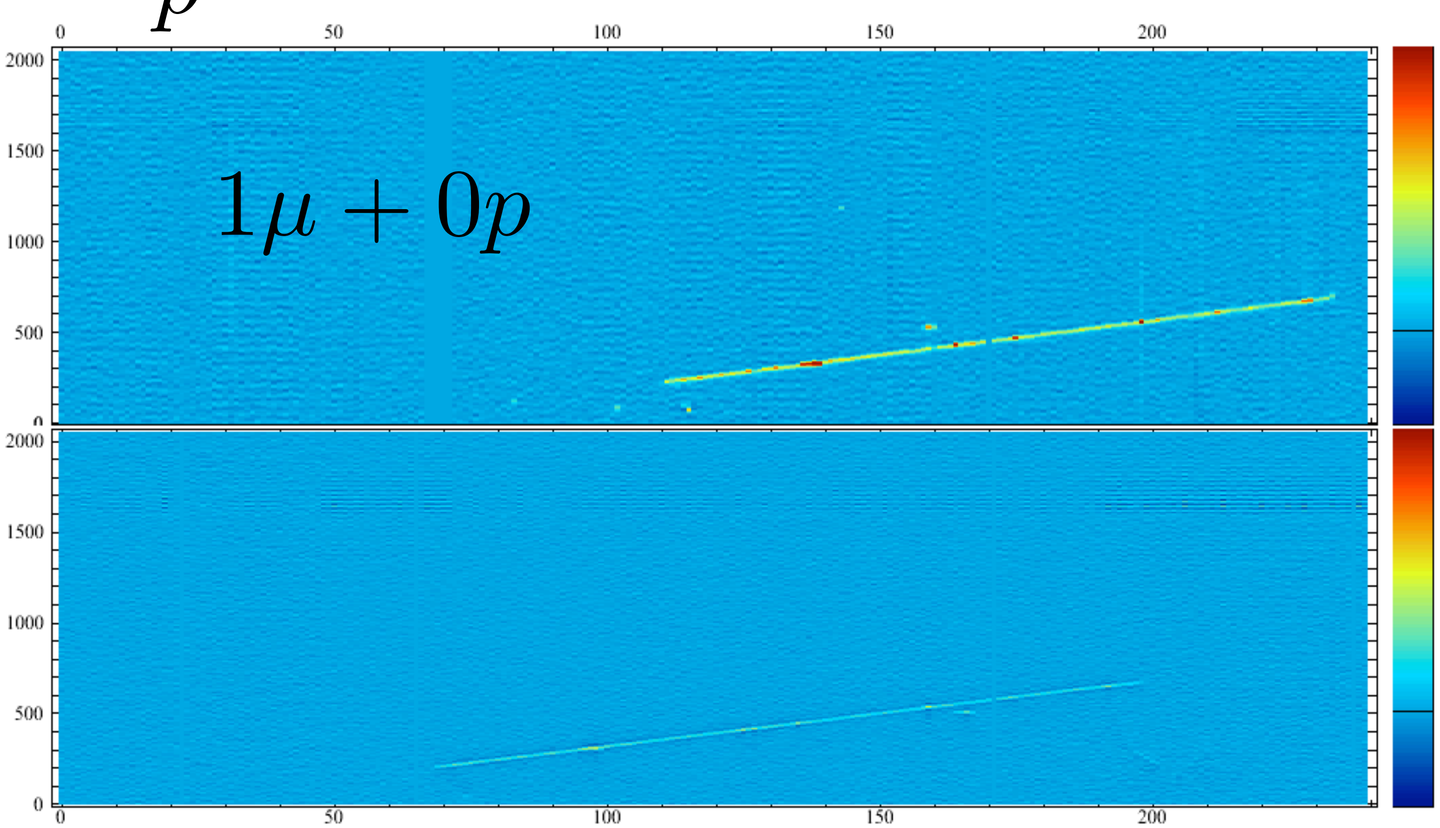
$1\mu + 0p$

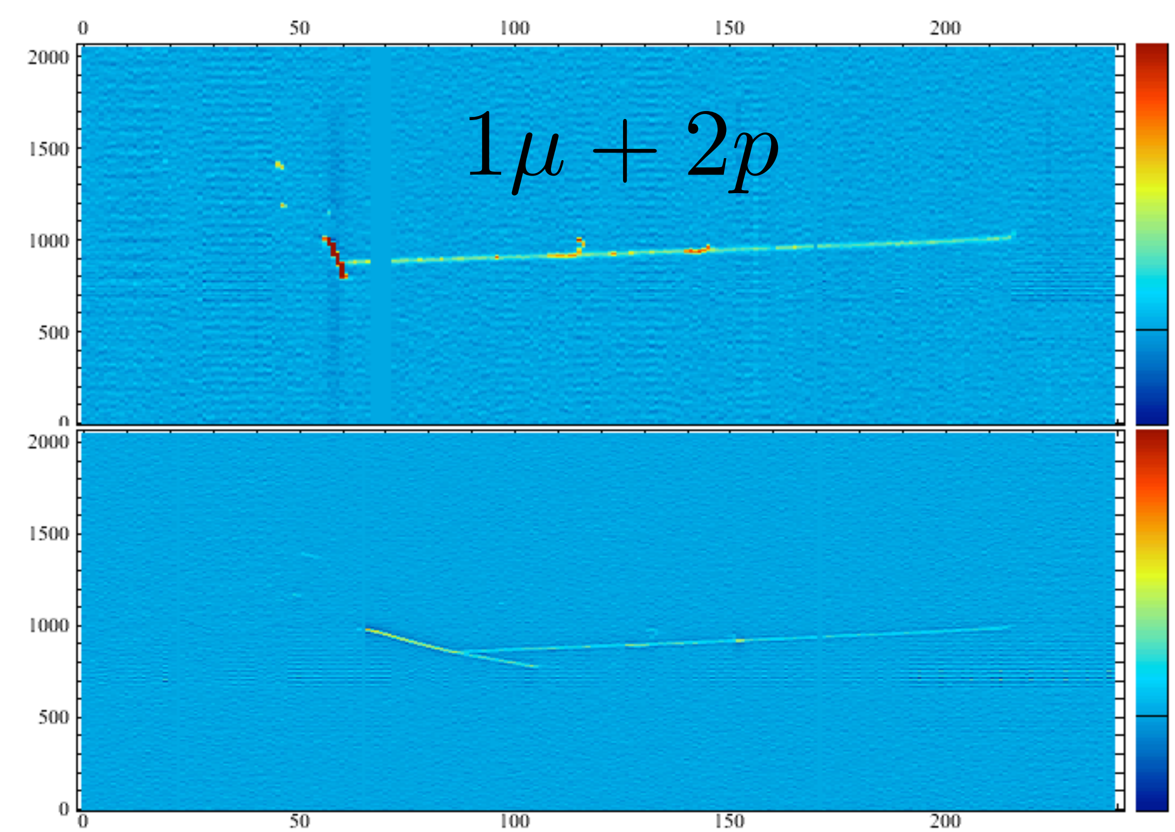
$1\mu + 1p$

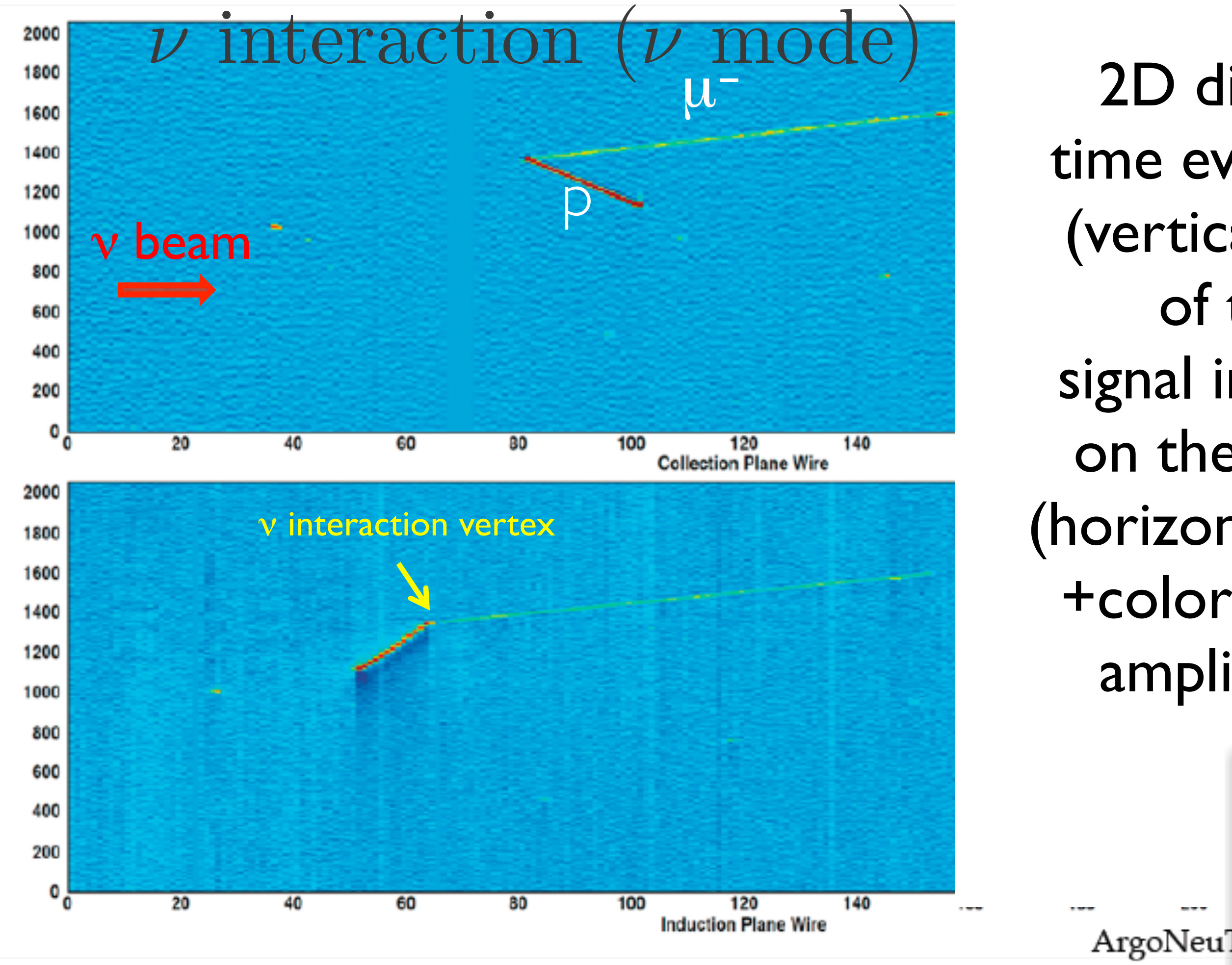
$1\mu + 2p$

$1\mu + 3p$



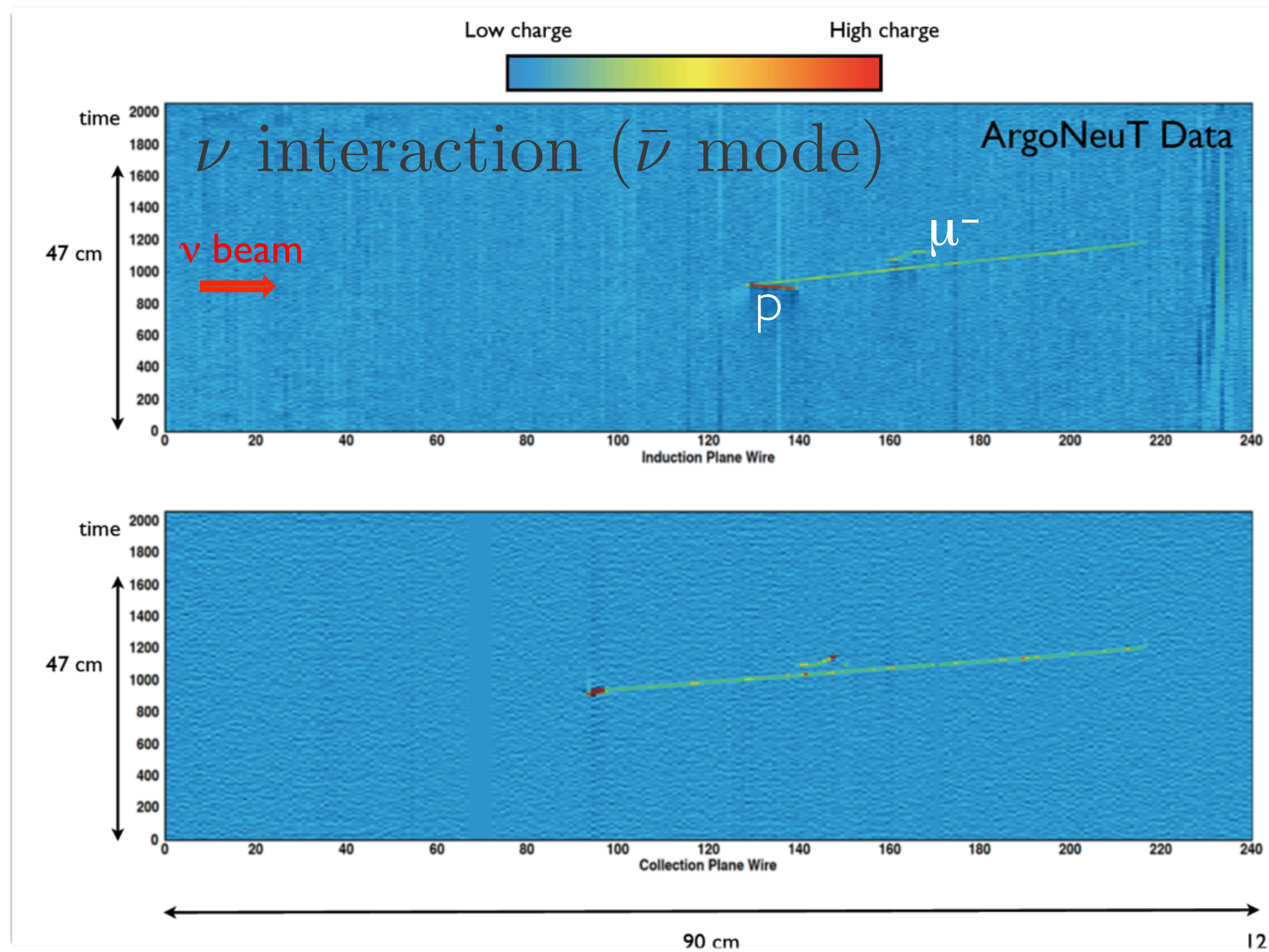






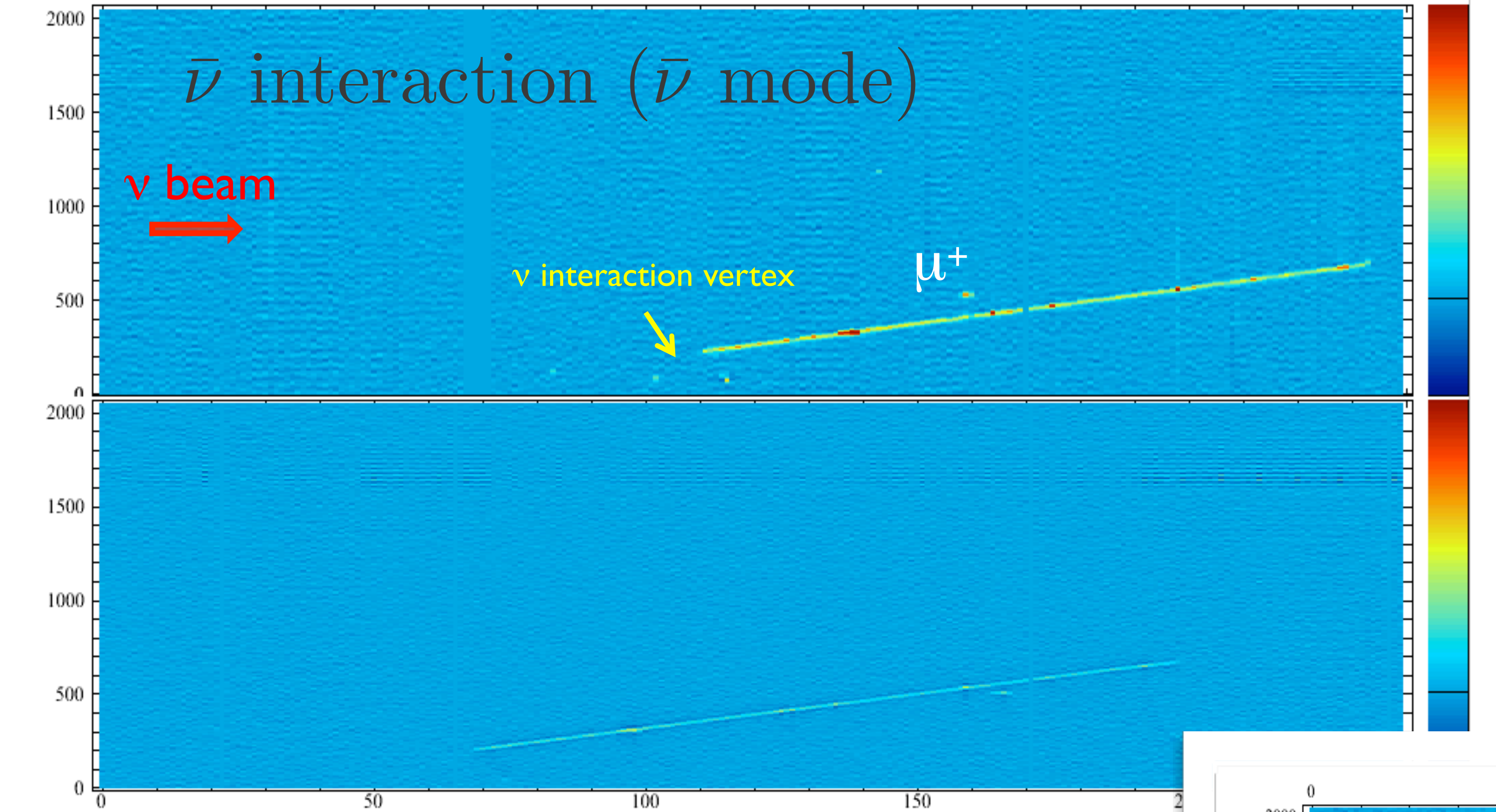
2D display:
time evolution
(vertical axis)
of the
signal induced
on the wires
(horizontal axis)
+color (signal
amplitude)

“standard” interaction in neutrinos

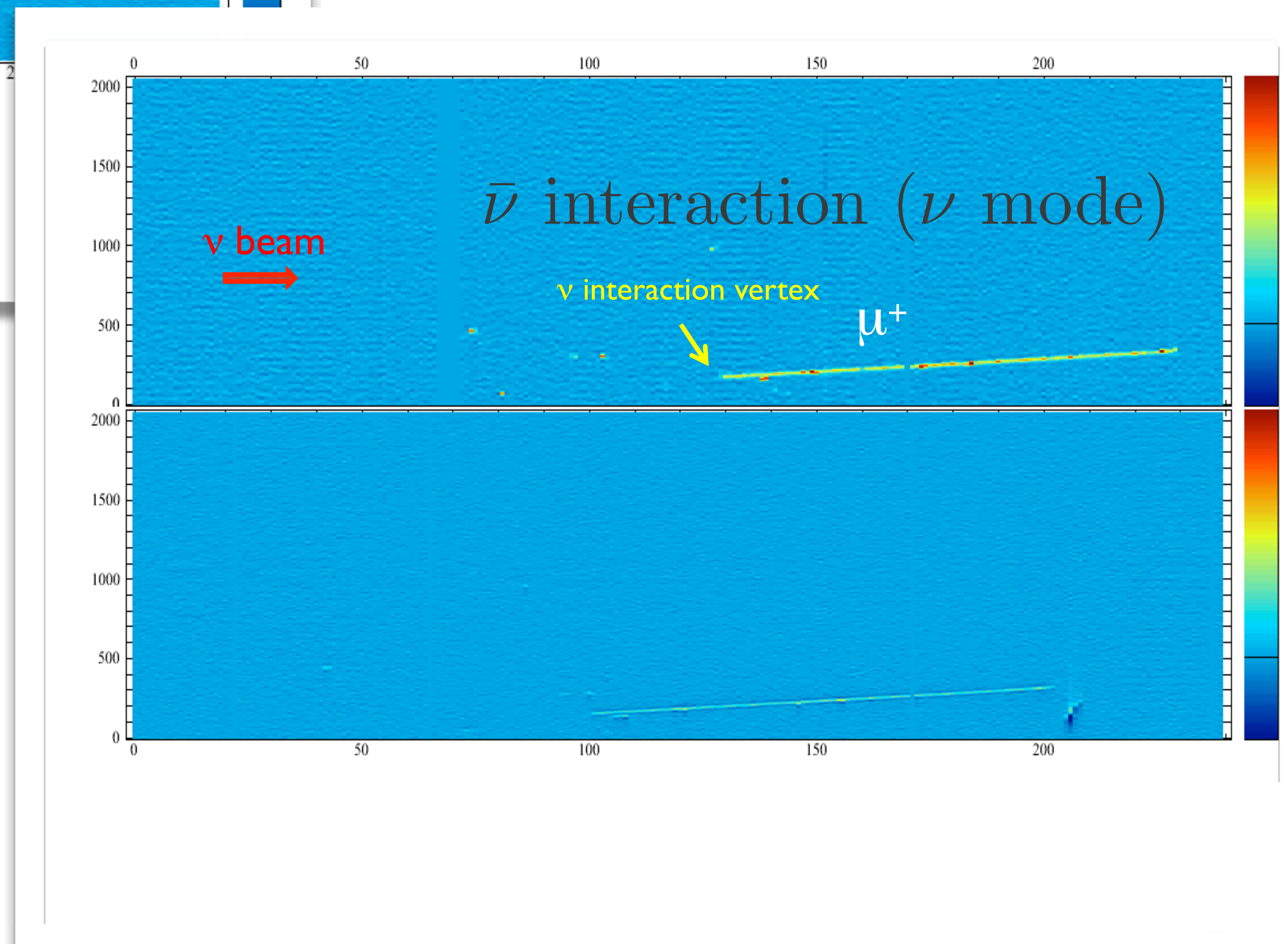


2 tracks: $\mu^- p$

ν_μ CC events: $\mu^- p$



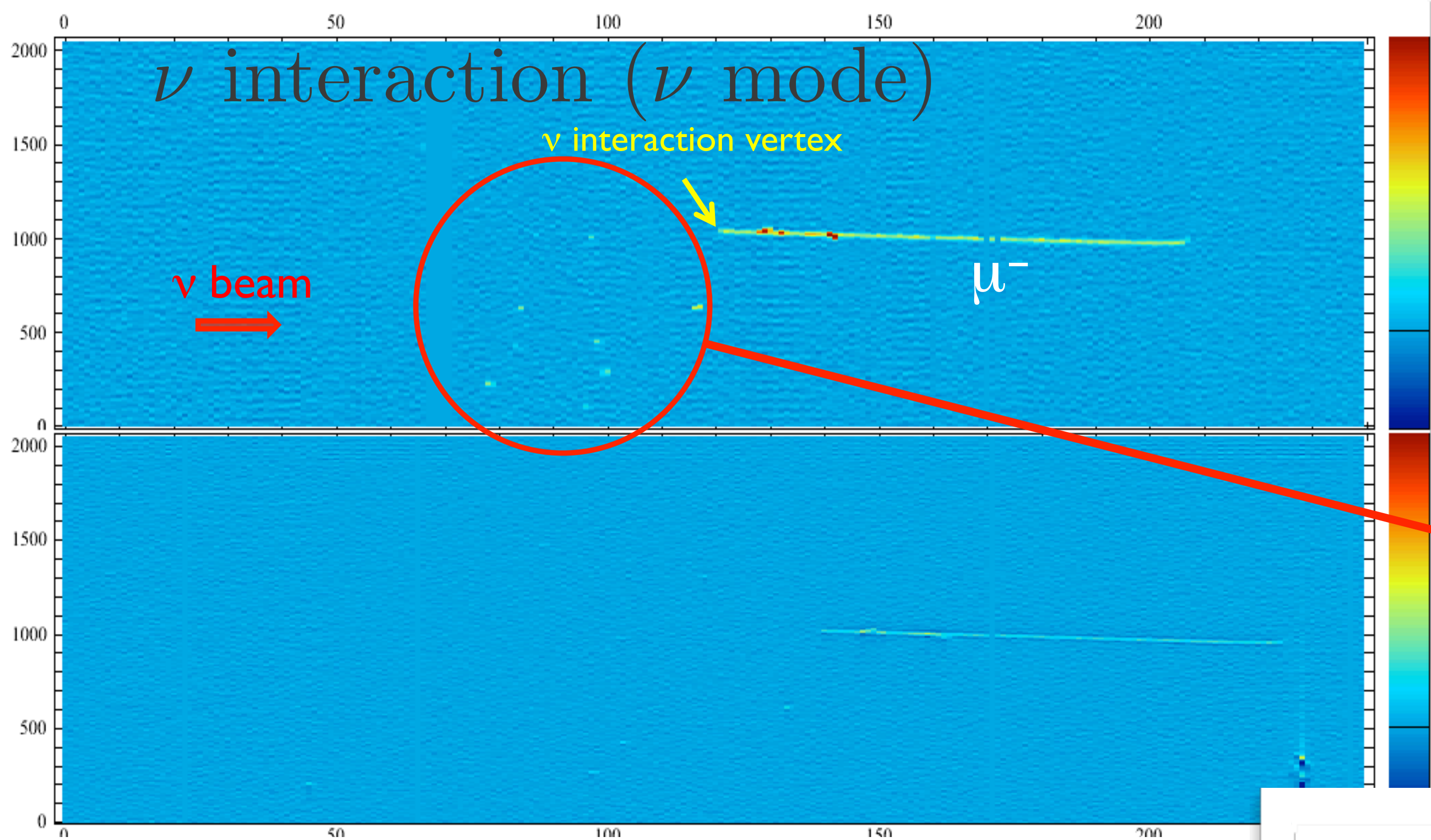
“standard” interaction in anti-neutrinos



1 track: μ^+

$\bar{\nu}_\mu$ CC events: μ^+n(0p)

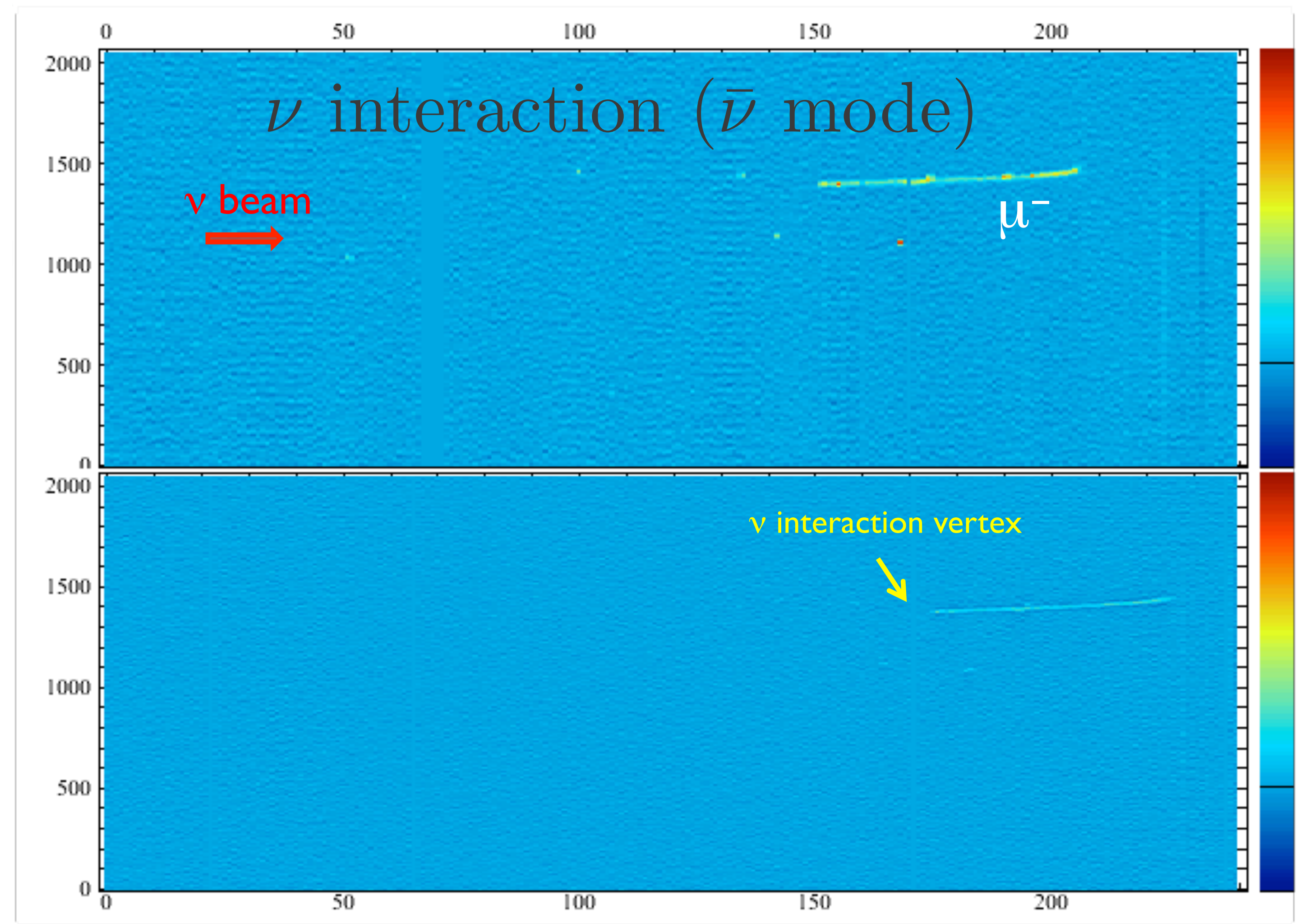
$\mu^{+/-}$ Np events
showing evidence of FSI
and/or
multi-nucleon production (or other effects)



"nonstandard" interaction

Activity around the vertex

e's from nuclear de-excitation γ conversion

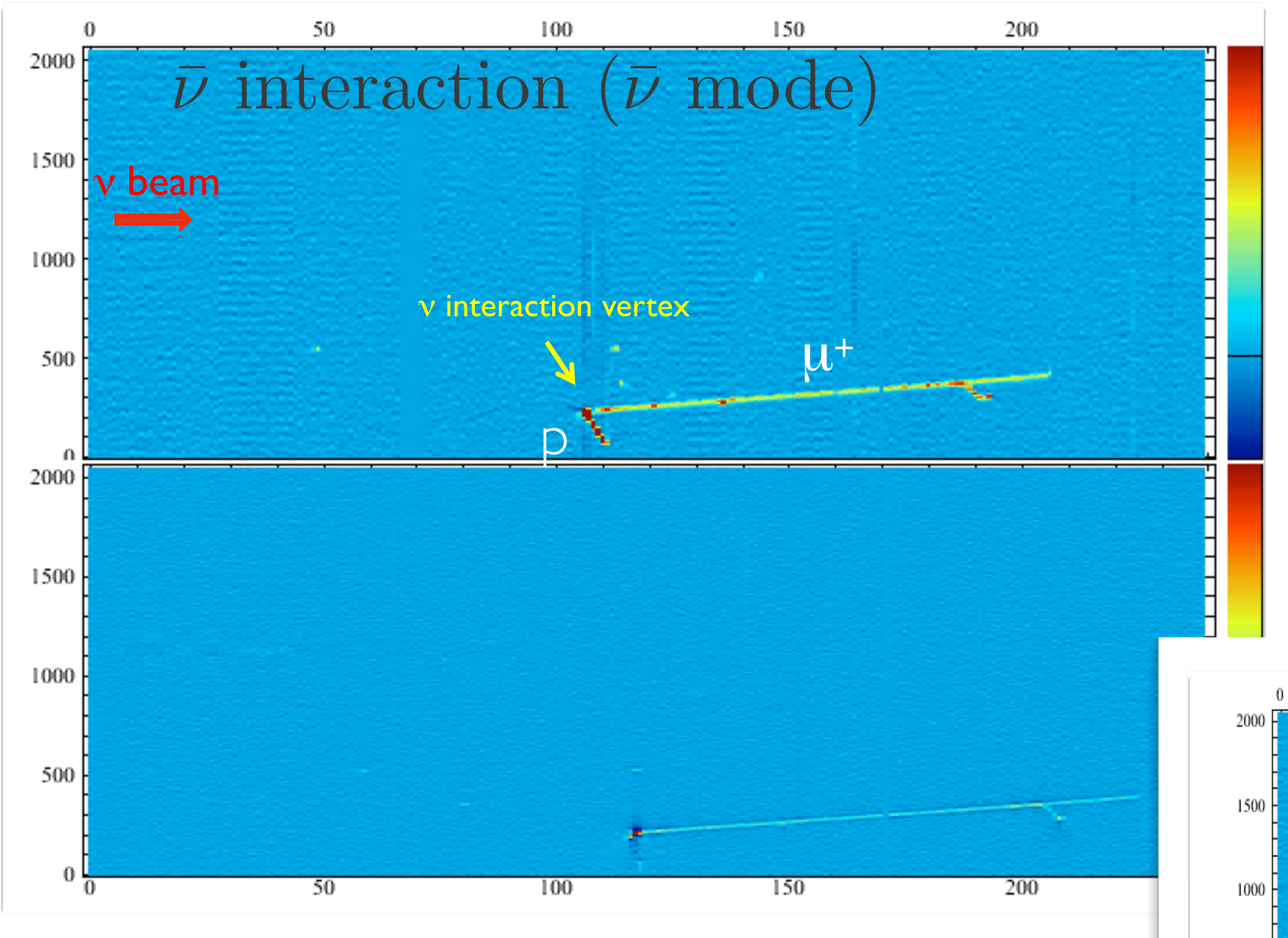


1 track: μ^-

μ^- track only, no p at the vertex

Evidence of FSI!

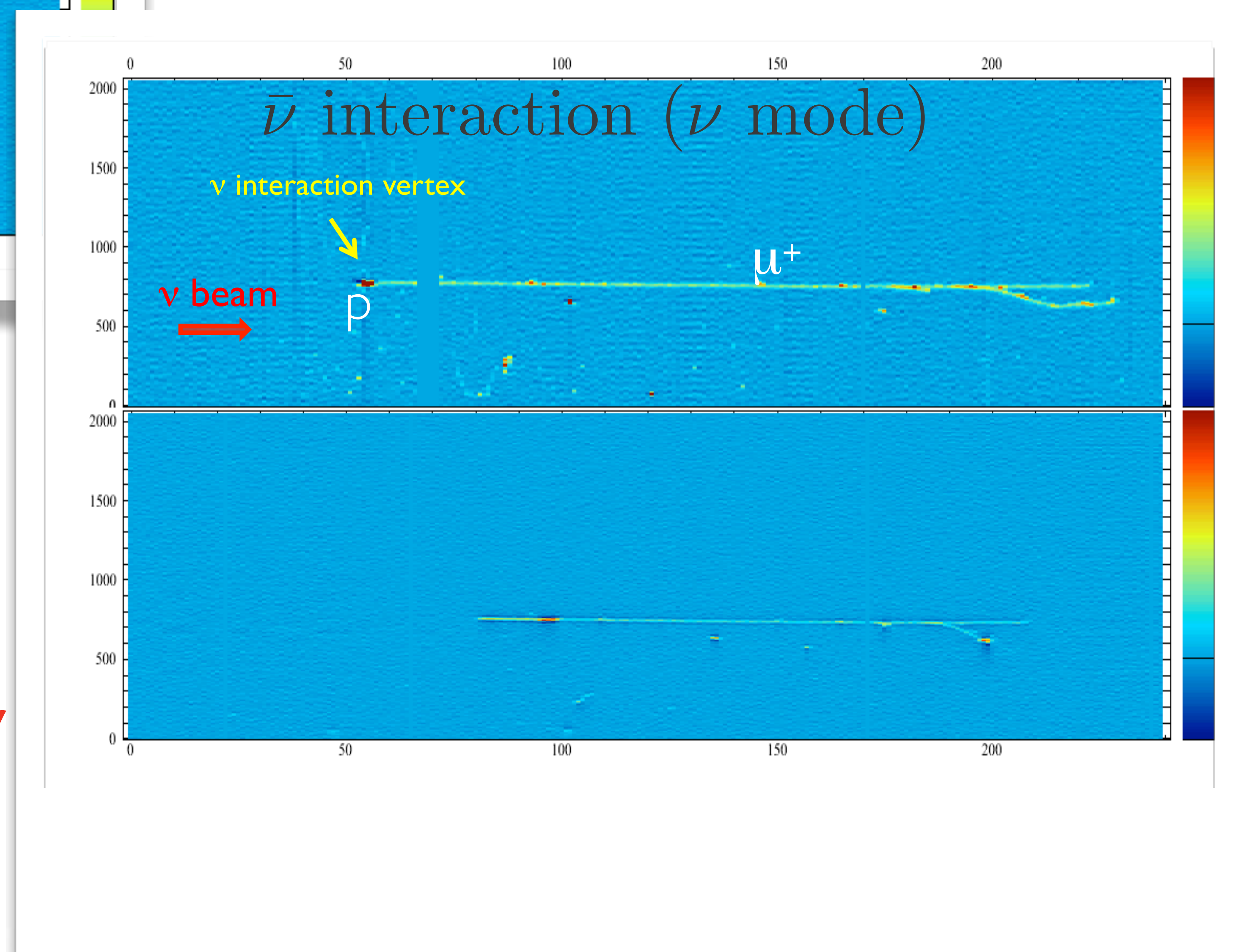
ν_μ CC events: μ^-0p



“nonstandard” interaction

Activity around the vertex

e's from nuclear de-excitation γ conversion



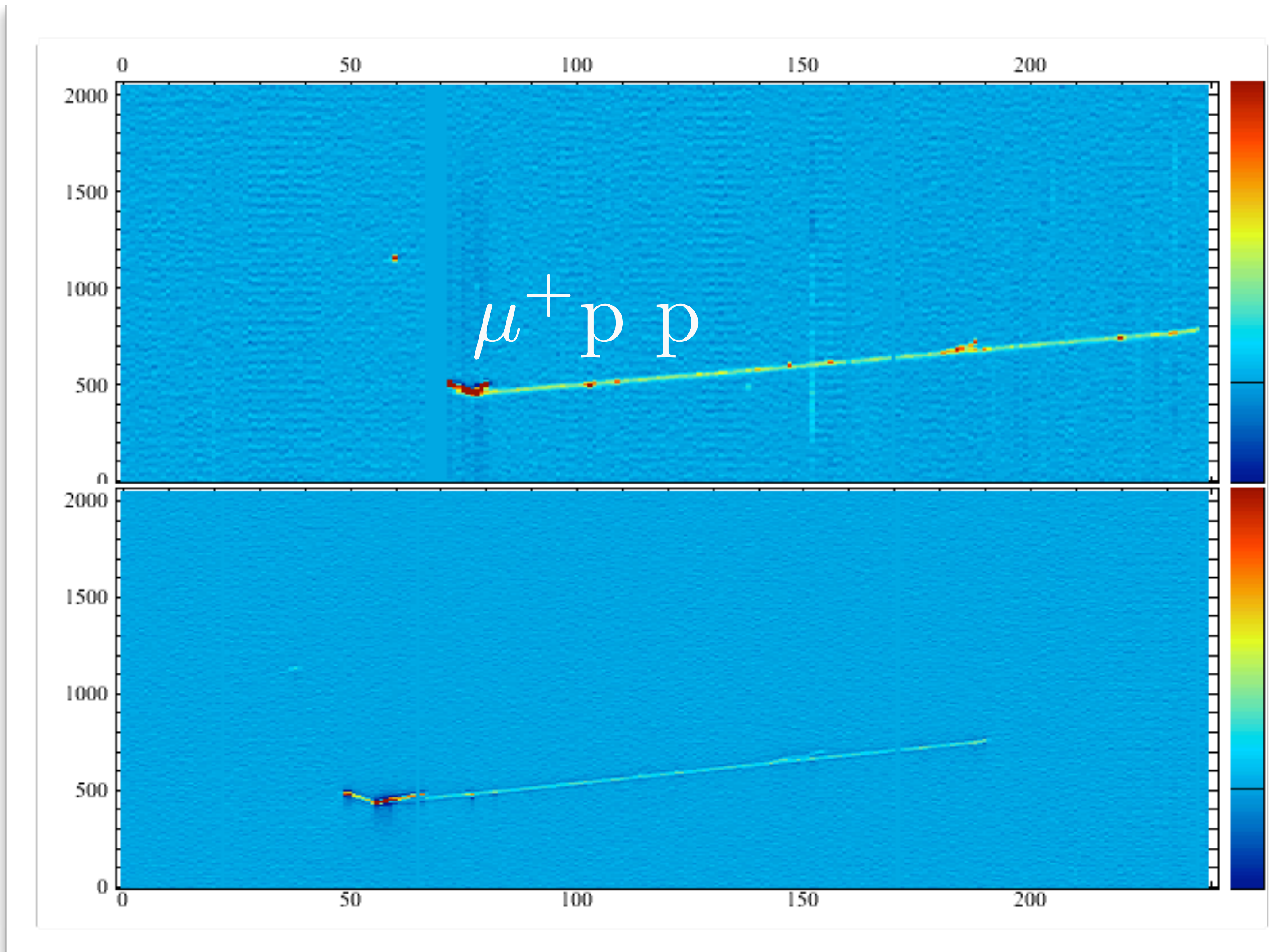
2 tracks: 1 μ^+ 1 p

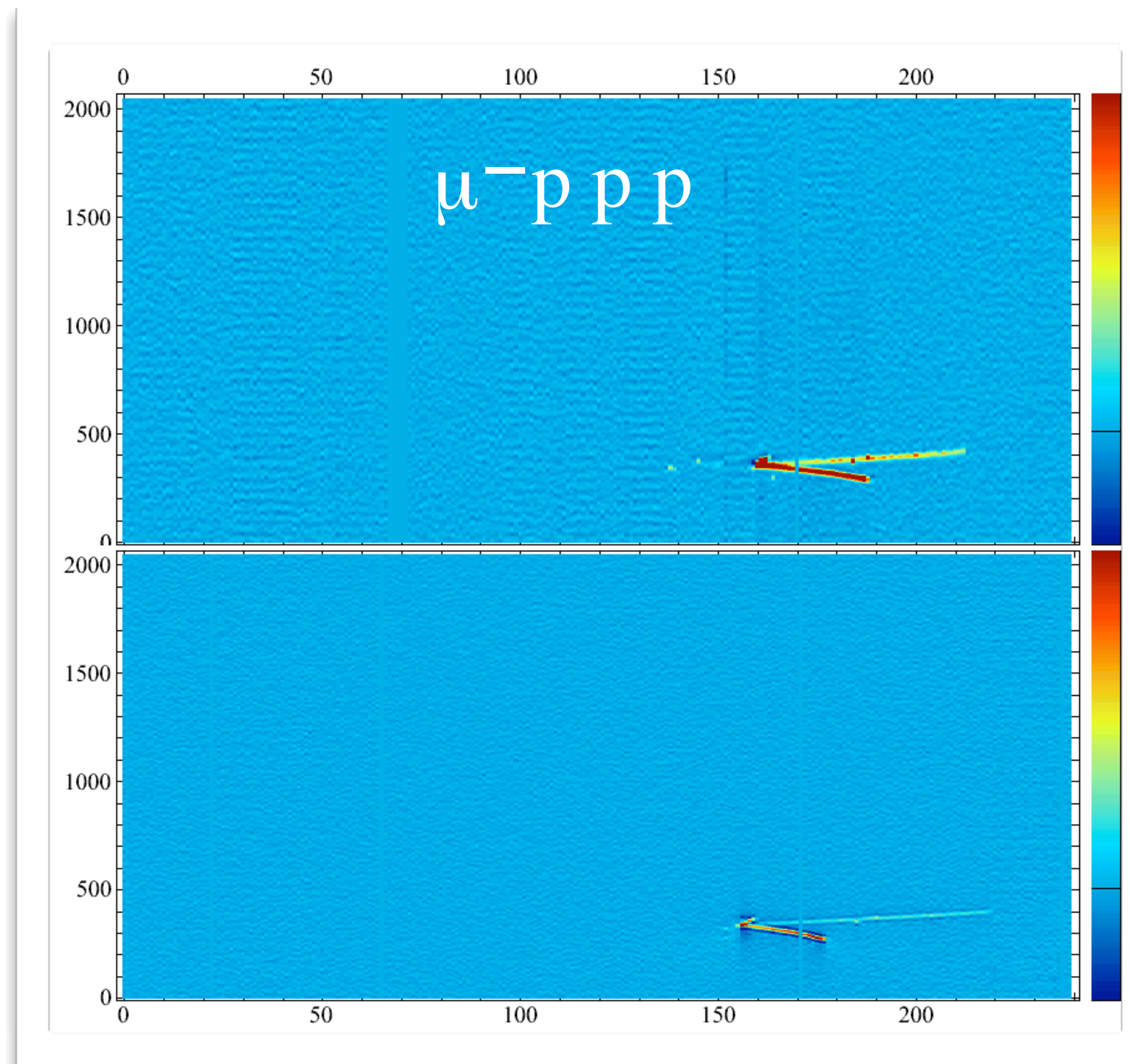
Evidence of FSI!

$\bar{\nu}_\mu$ CC events: μ^+p

Multi-p accompanying
the leading muon
$+\gamma$ activity in the volume
around the vertex

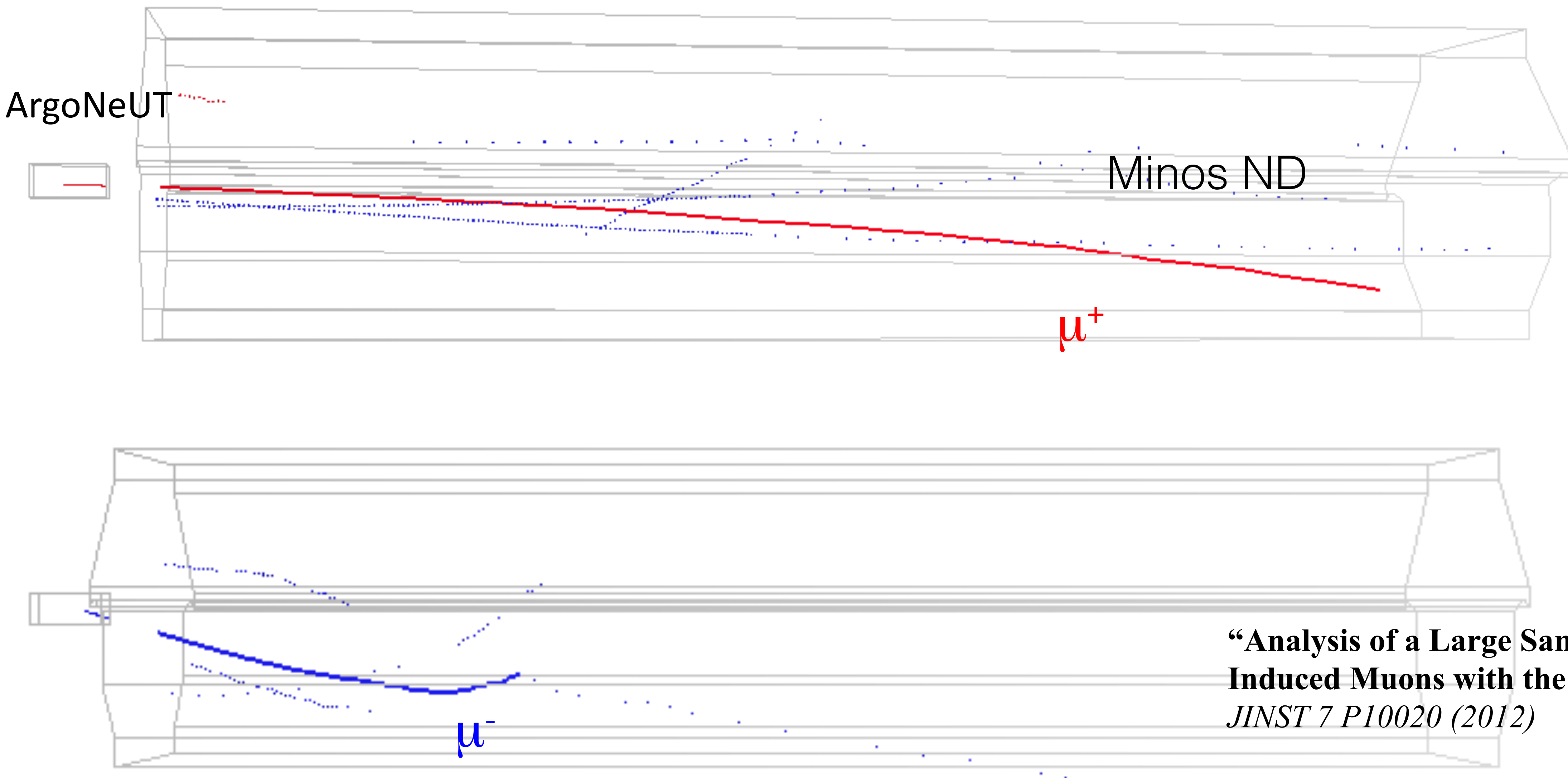
"nonstandard" interaction





$\nu_\mu/\bar{\nu}_\mu$ CC events: $\mu^{-/+}$multi-proton

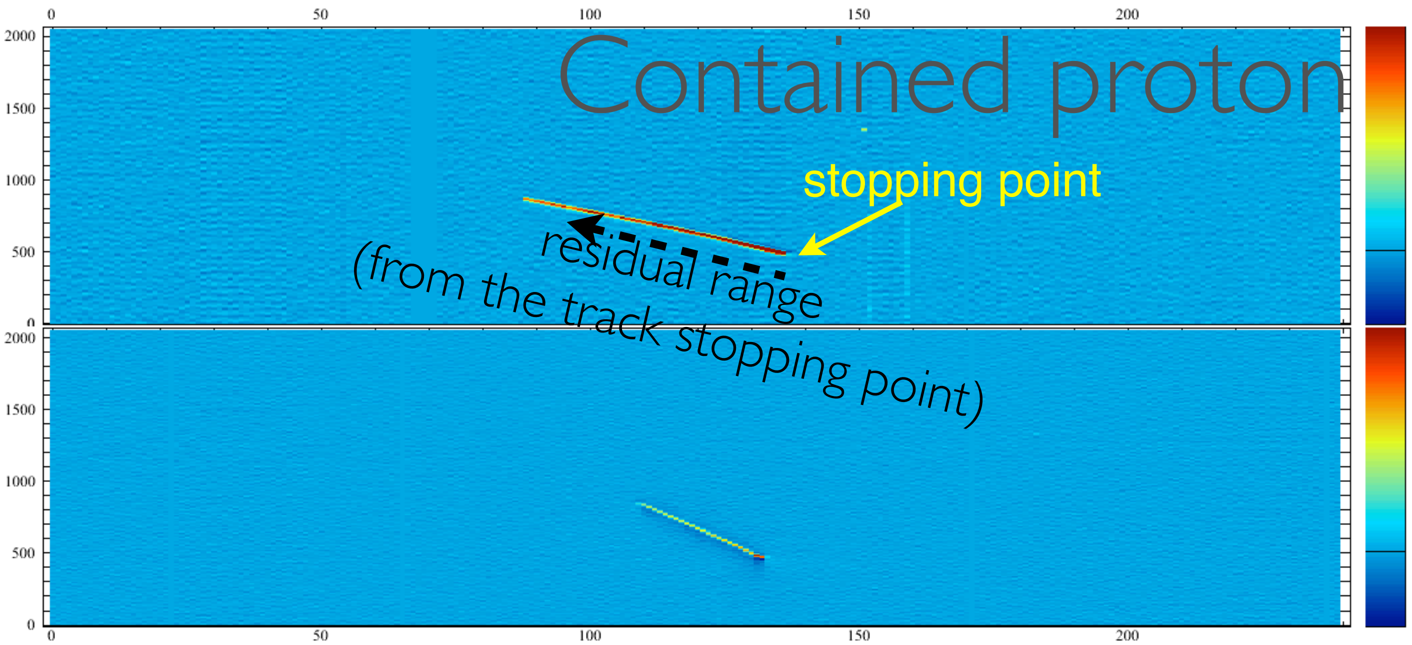
Muon Reconstruction

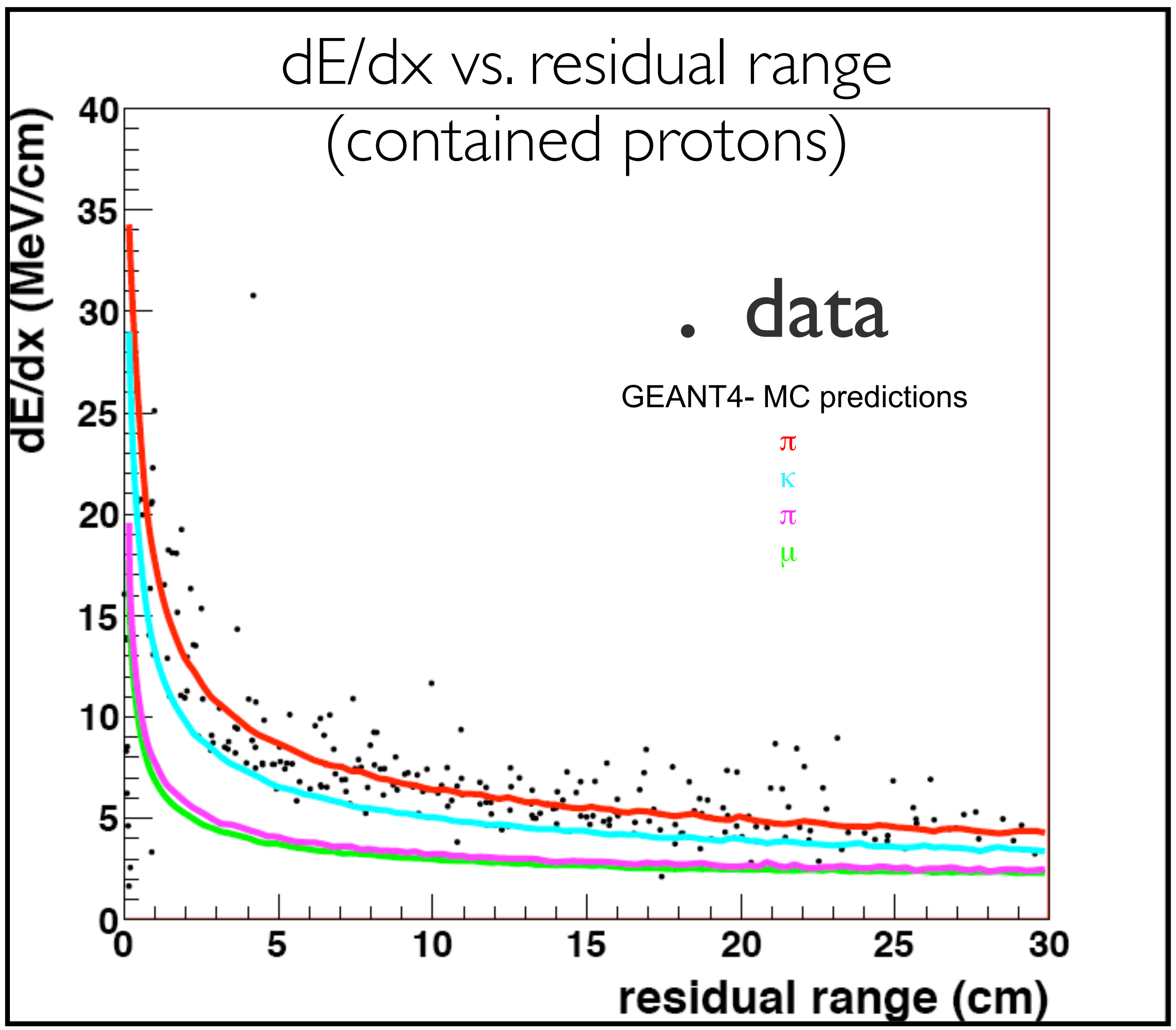


"Analysis of a Large Sample of Neutrino-Induced Muons with the ArgoNeuT Detector"
JINST 7 P10020 (2012)

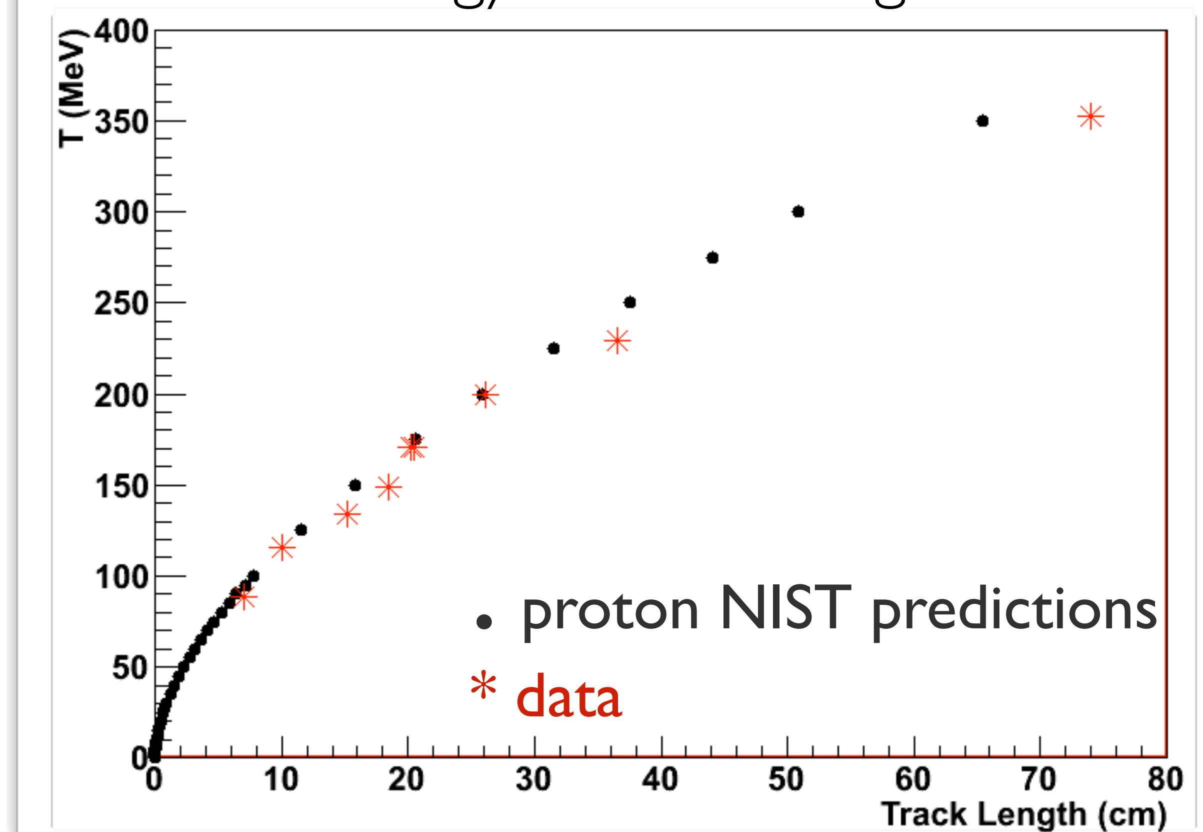
muon kinematics: ArgoNeuT 3D, ArgoNeuT calorimetric reconstruction + MINOS ND measurement (momentum and sign)

STOPPING PARTICLE - CALORIMETRIC RECONSTRUCTION and PID





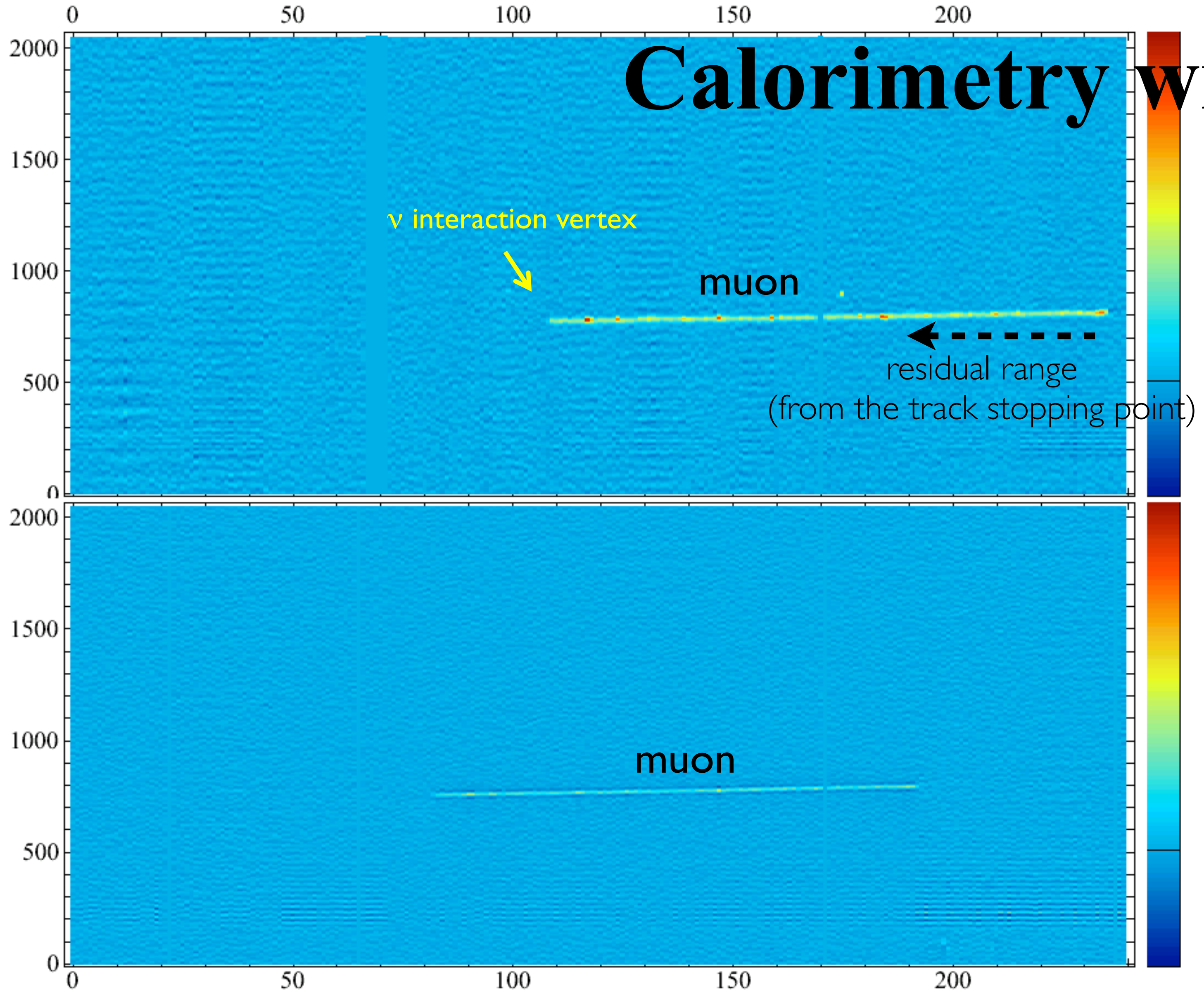
Kinetic Energy vs. track length



Measurement of:

- dE/dx vs. residual range along the track
- kinetic energy vs. track length

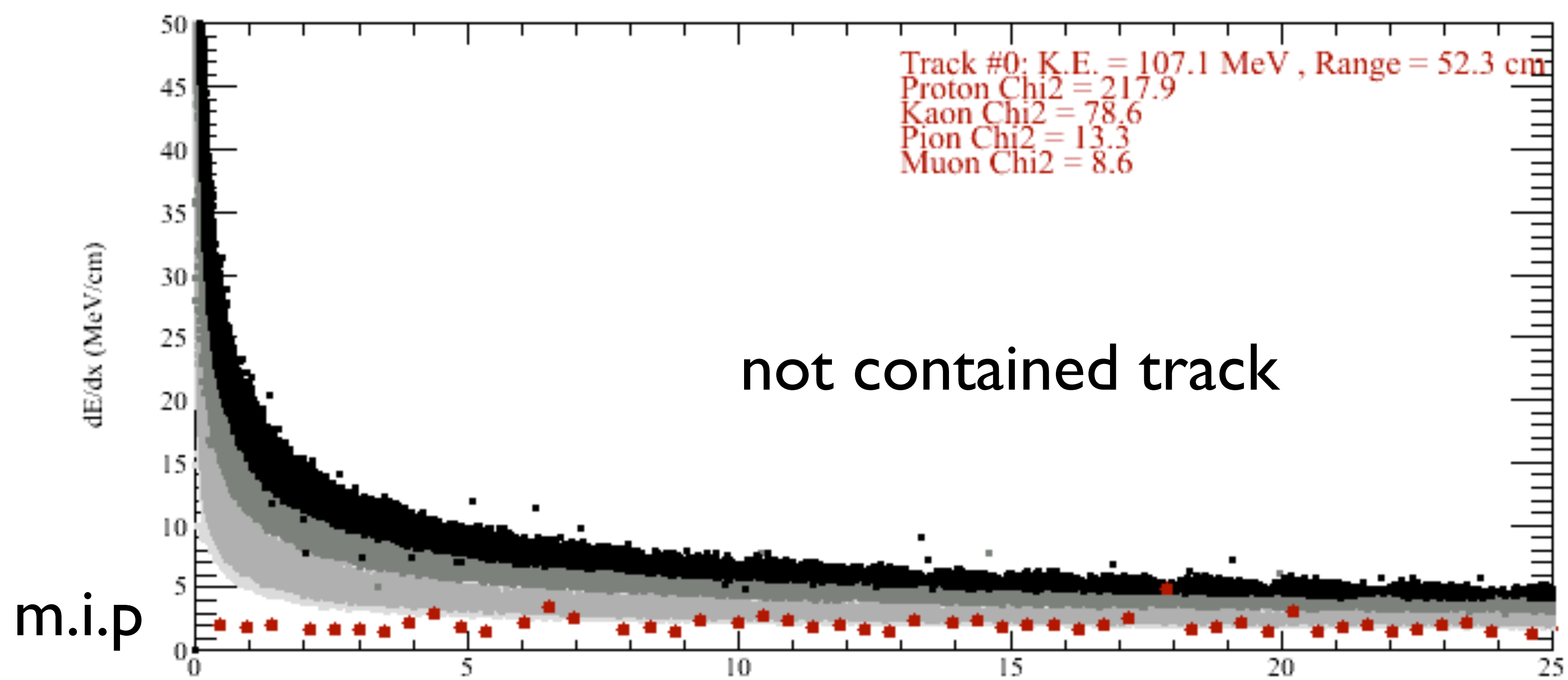
Calorimetry with muon



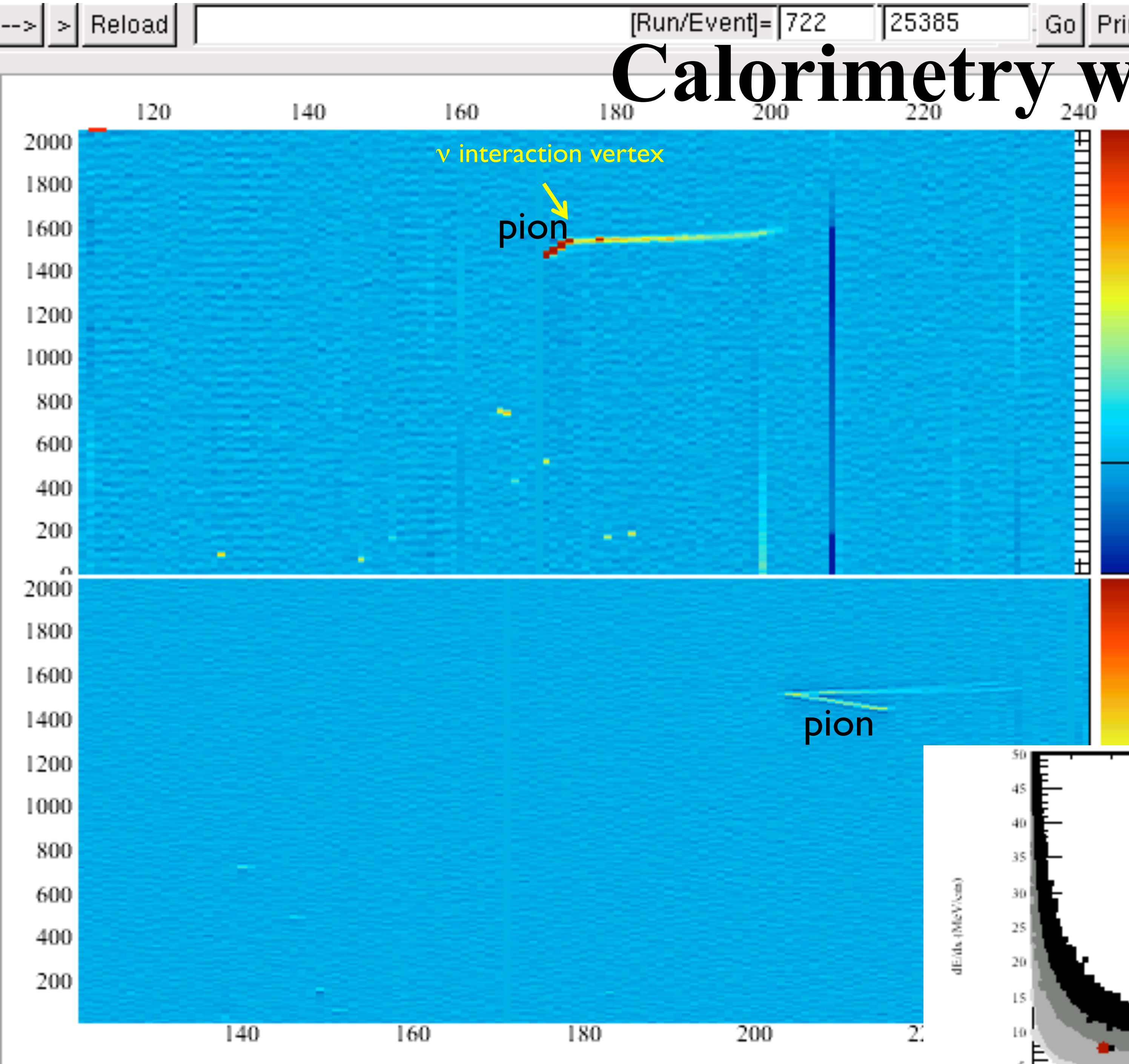
0p event

dE/dx vs. residual range

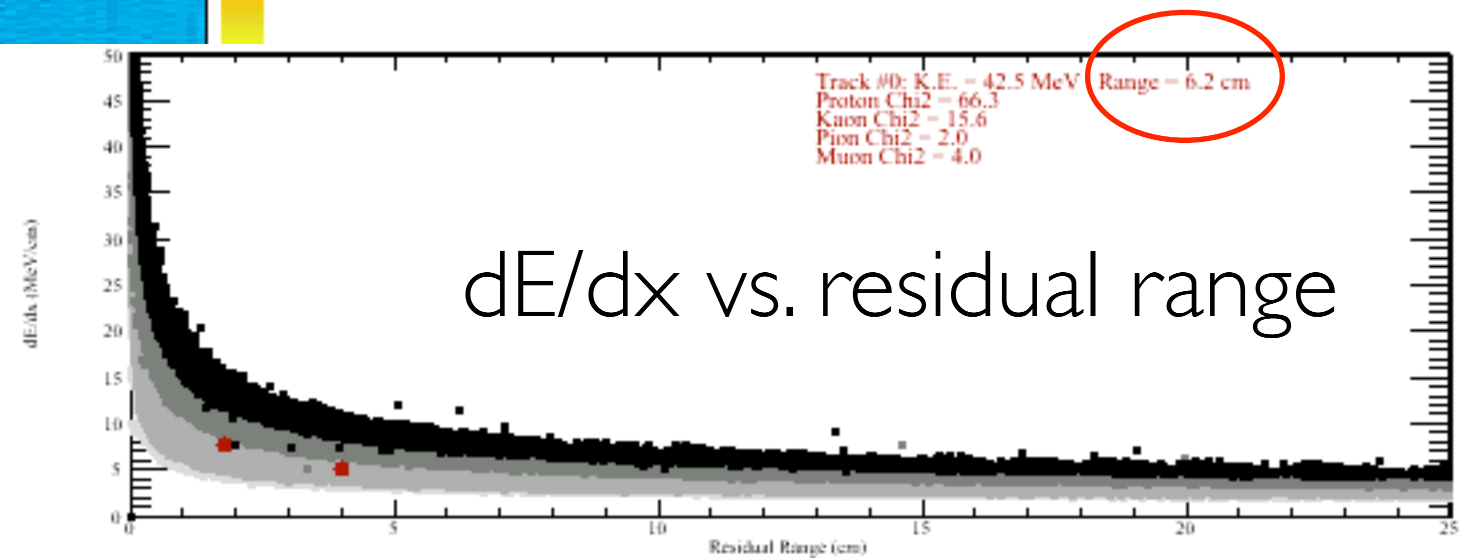
not contained muon (m.i.p.): flat dE/dx vs. res. range



Calorimetry with pion

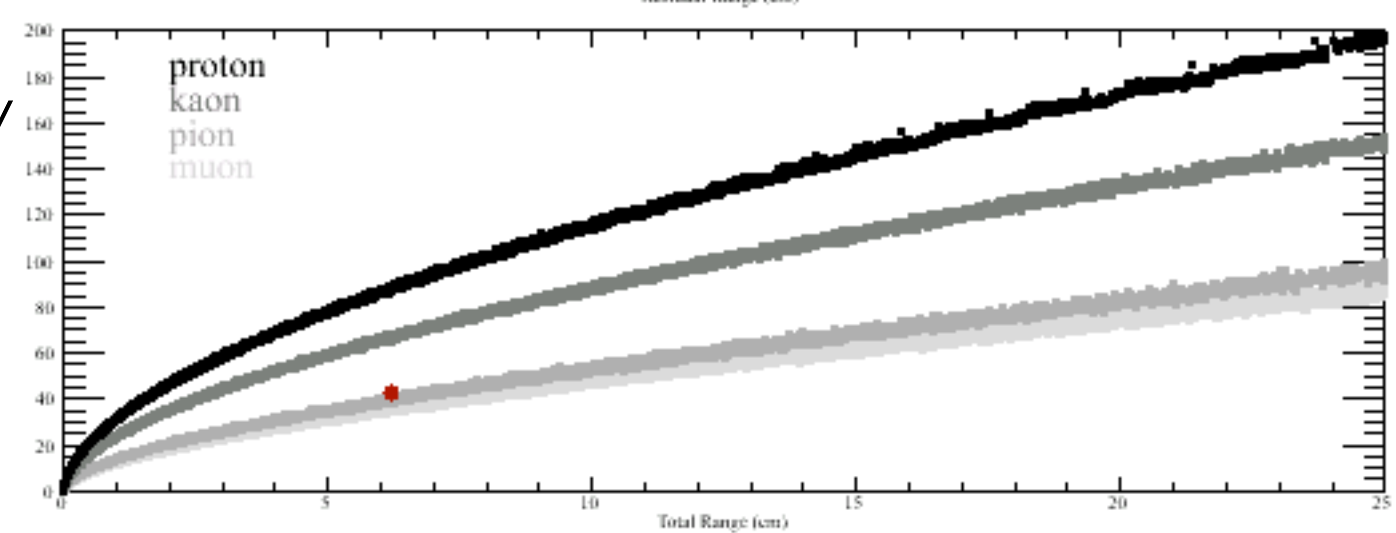


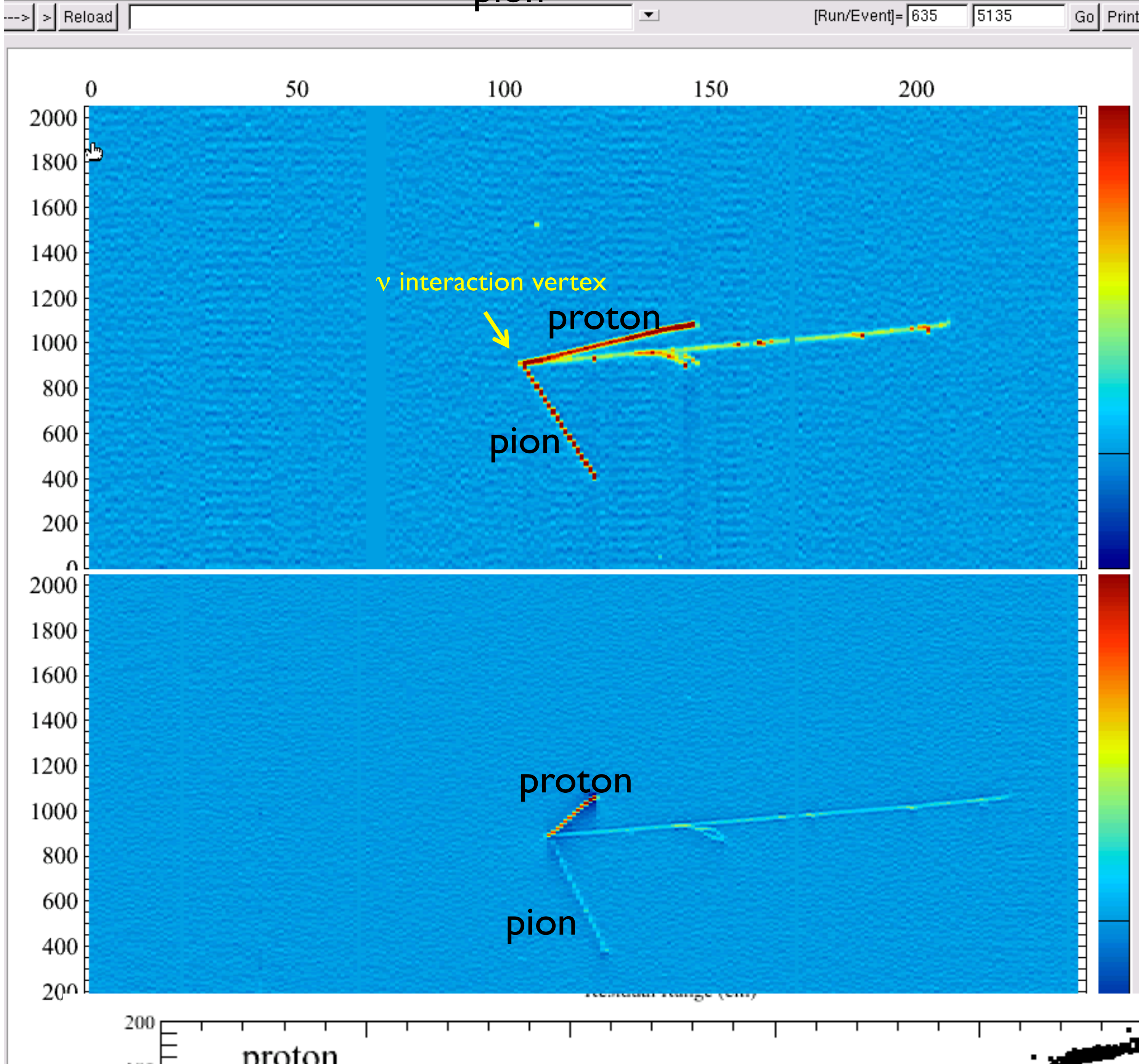
6 cm Pion!

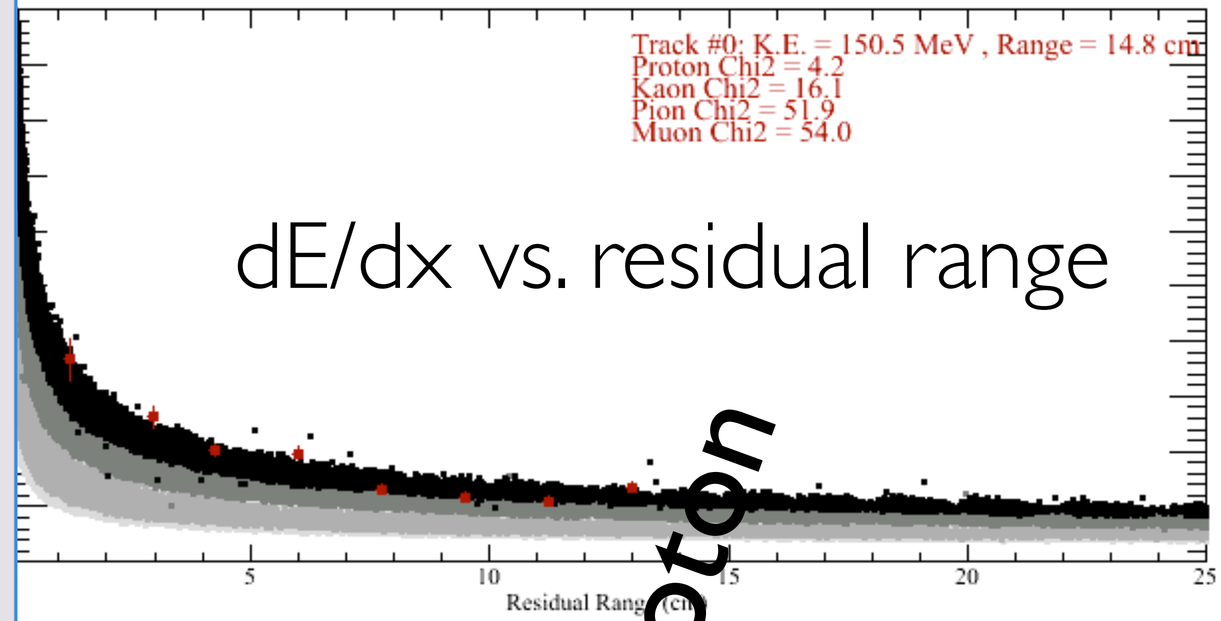


dE/dx vs. residual range

Kinetic energy
vs.
track length

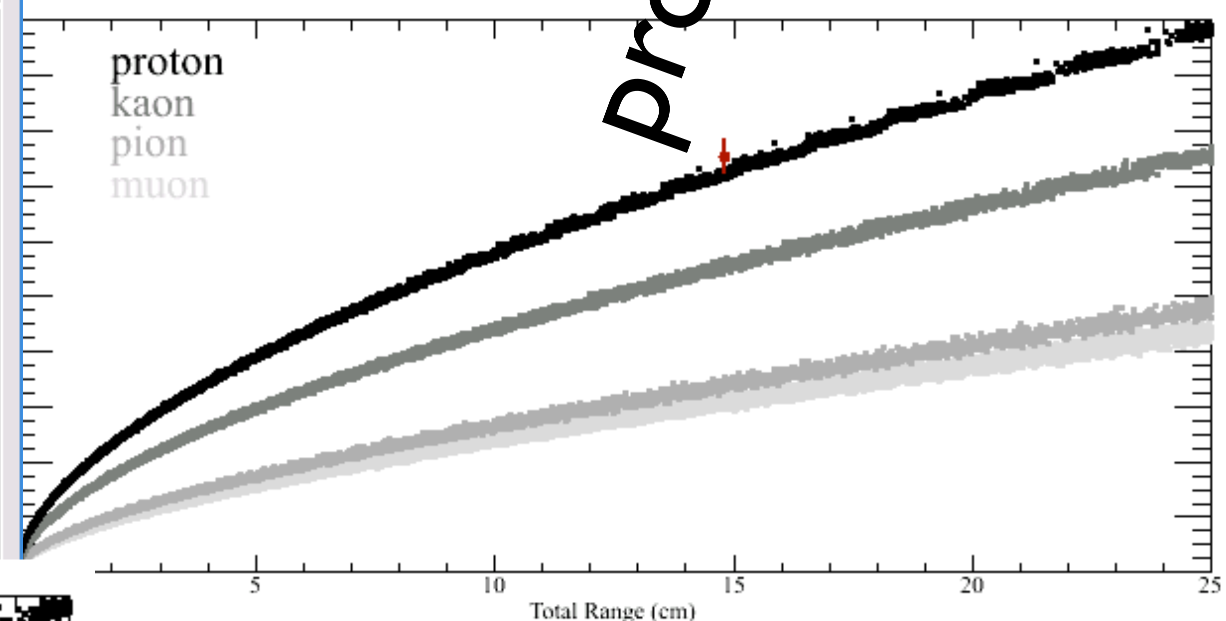


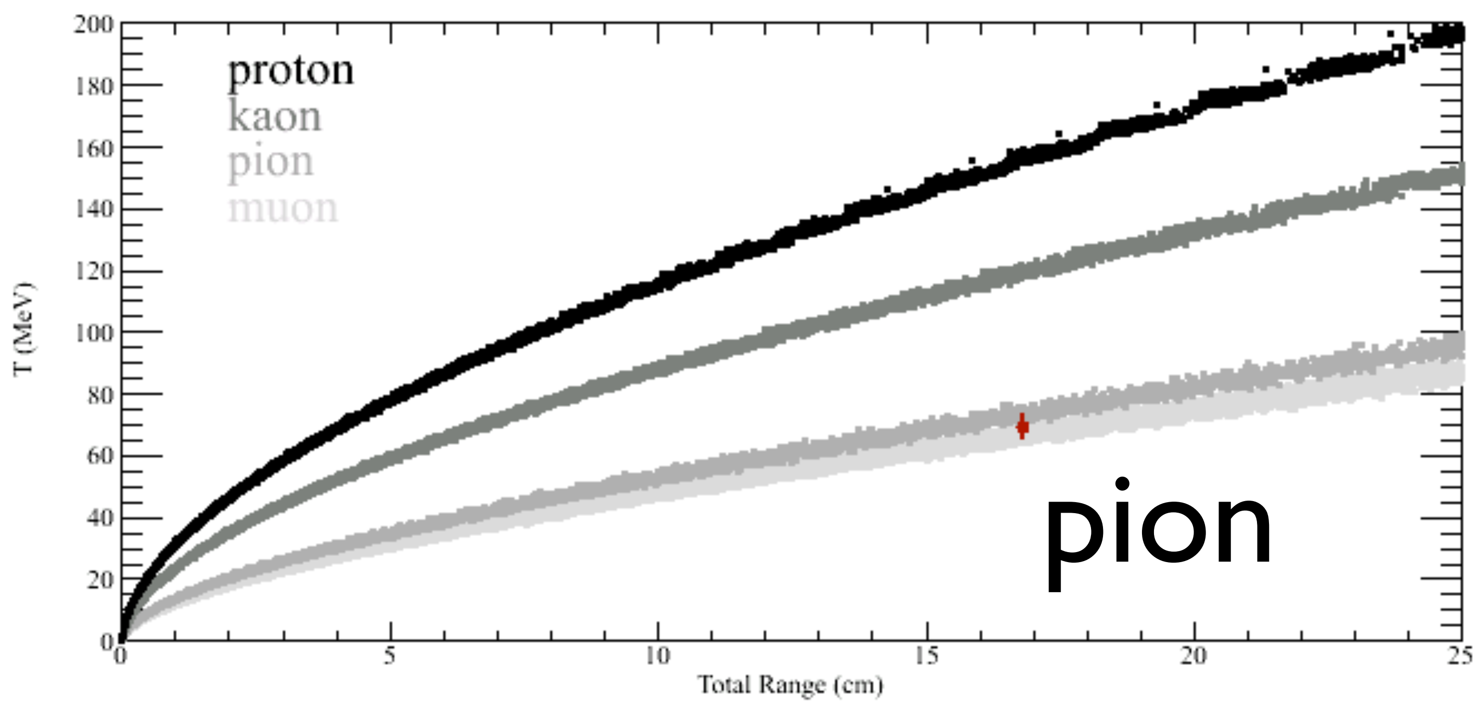




dE/dx vs. residual range

proton





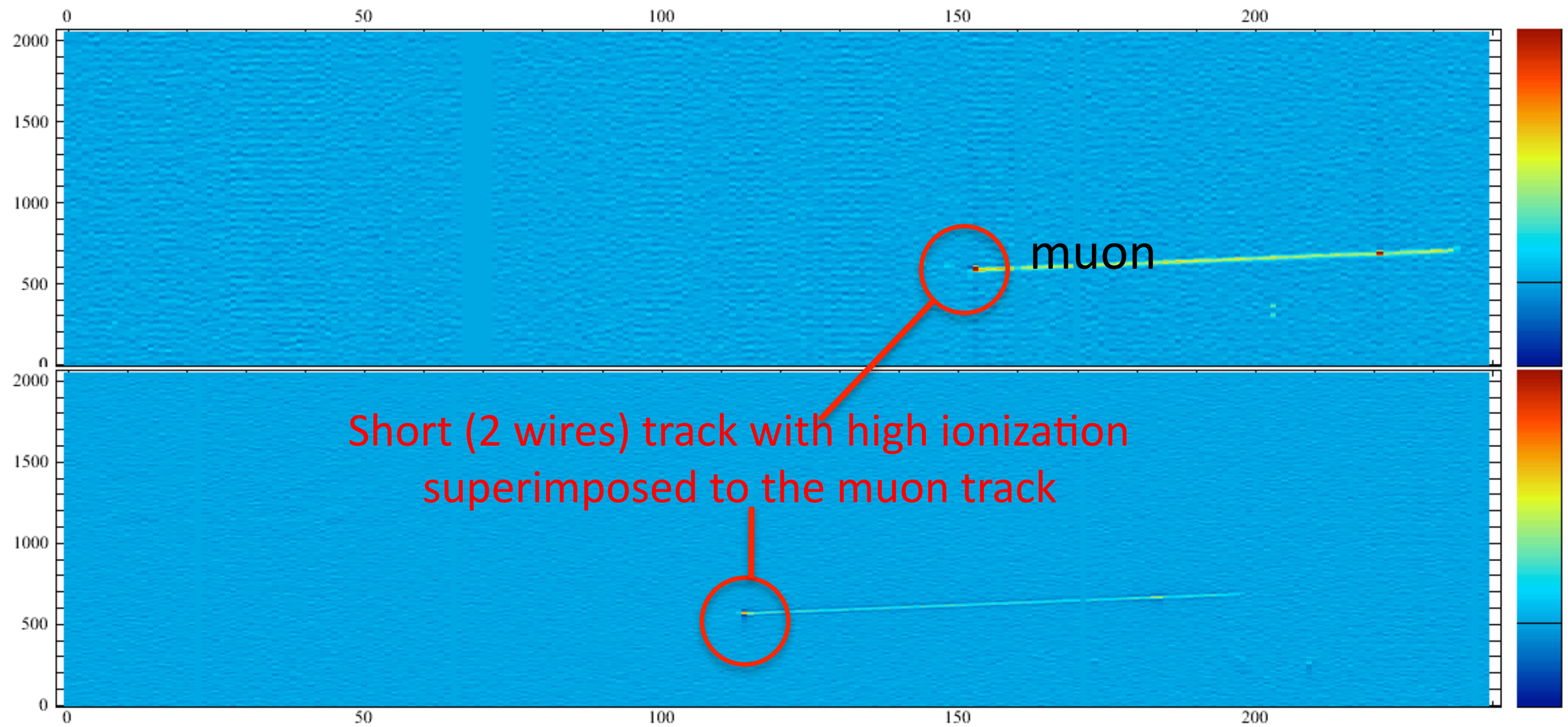
pion

Kinetic energy

vs.

track length

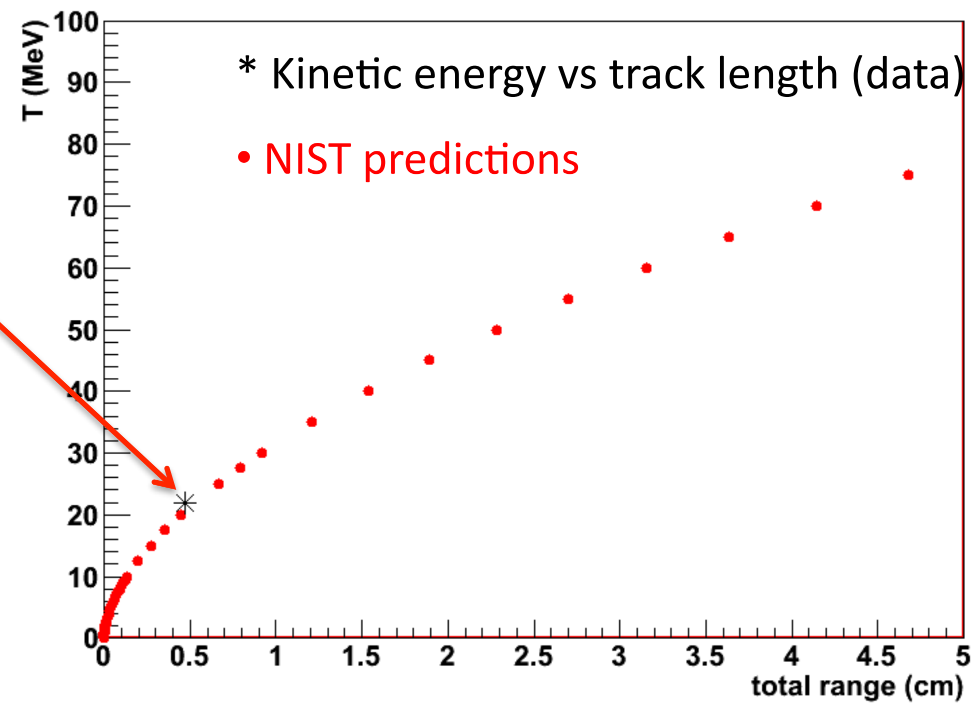
Example of Low Energy Proton Reconstruction



The short track behaves like proton

Length=0.5 cm

KE=22±3 MeV



proton threshold is 21 MeV of Kinetic Energy

Data Analysis still in progress
Preliminary Results!

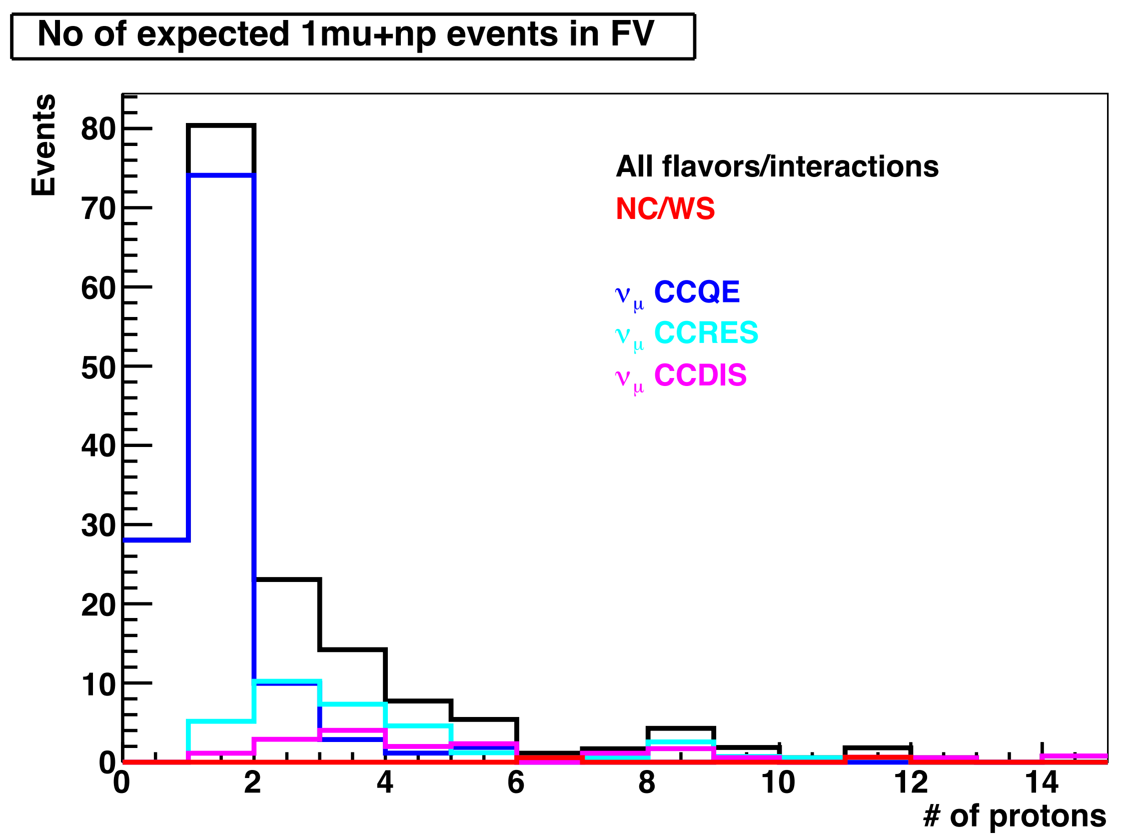
Note: Flux in anti-neutrino needs to be studied (no uncertainties included)
MC used for comparison with data: GENIE v3665
Analysis has been focused on lower multiplicity proton events!
(No optimization for higher multiplicities at the moment- in progress)
More in depth studies of background effects are ongoing and will be finalized soon

Data-MC comparison

ν_μ - neutrino mode run

Multiplicity	Genie Expectation *	Genie % of Total	DATA**	DATA % of Total
0p+1mu	28±4	16%	15±3	14%
1p+1mu	80±7	47%	51±10	48%
2p+1mu	23±4	13.4%	28±6	26%
3p+1mu	14±3	8.3%	13±3	12%
4p+1mu	8±2	4.5%	0	0
TOTAL (including >4p)	172±10	-	107±12	-

Data 38% lower



*statistical errors
** stat.+syst. errors- preliminary

μ^- Np events - MC predictions (II) GENIE-FLUKA comparison

with 21 MeV proton threshold

μ^- GENIE v3665

Multiplicity	% of Total	% not CCQE
1mu+0p	16.3	0
1mu+1p	47	7.8
1mu+2p	13.4	57
1mu+3p	8.3	80
1mu+4p	4.5	85
1mu+5p	3	65
1mu+6p	0.6	100
1mu+7p	1	100
1mu+8p	2.5	100
1mu+9p	1	70
1mu+10p	0.3	100

μ^- FLUKA*

Multiplicity	% of Total	% not CCQE
1mu+0p	16.5	2.7
1mu+1p	51.2	10
1mu+2p	16.4	73
1mu+3p	10.8	93
1mu+4p	3.6	95
1mu+5p	1.1	97
1mu+6p	0.28	97
1mu+7p	0.08	99
1mu+8p	0.02	100
1mu+9p	0.008	97
1mu+10p	0.003	100
1mu+Np		33

MC agreement on % of total, but very different % of not CCQE (could be as large as ~30%, according to MC)

*kindly from G. Battistoni (priv. comm.)

μ- Np events - MC predictions (II)
GENIE-FLUKA comparison

21 MeV proton threshold

μ⁻ GENIE v3665

Multiplicity	% of Total	% not CCQE
1mu+0p	16.3	0
1mu+1p	47	7.8
1mu+2p	13.4	57
1mu+3p	8.3	80
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1mu+5p	3	65
1mu+6p	0.6	100
1mu+7p	1	100
1mu+8p	2.5	100
1mu+9p	1	70
1mu+10p	0.3	100

μ⁻ FLUKA*

Multiplicity	% of Total	% not CCQE
1mu+0p	16.5	2.7
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1mu+3p	10.8	93
1mu+4p	3.6	95
1mu+5p	1.1	97
1mu+6p	0.28	97
1mu+7p	0.08	99
1mu+8p	0.02	100
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1mu+10p	0.003	100
1mu+Np		33

MC agreement on % of total, but very different % of not CCQE
(could be as large as ~30%, according to MC)

*kindly from G. Battistoni (priv. comm.)

GiBUU *

% of Total	% not CCQE
19.0	29
41.0	36.5
20	57
11.0	95
5.0	95
2.5	100
1.2	100
	51

Very different
% from not CCQE
(50%)!!

*thanks to O. Lalakulich for making simulations

ARGONEUT DATA-MC COMPARISON

ν_μ - NuMI neutrino mode run

Lots of infos not yet processed, e.g.

Multiplicity	Genie	Genie % of Total	DATA	DATA % of Total	DATA/MC ratio
0p+1mu	28±4	16%	15±3	14%	0.53
1p+1mu	80±7	47%	51±10	48%	0.63
2p+1mu	23±4	13.4%	28±6	26%	1.22
3p+1mu	14±3	8.3%	13±3	12%	0.93
4p+1mu	8±2	4.5%	0	0	
TOTAL (including >4p	172±10	-	107±12	-	0.62

$(0p/1p)_{DATA}=0.29$
$(0p/1p)_{GENIE\ MC}=0.35$
$(0p/1p)_{FLUKA}=0.32$

DATA-MC quite in agreement on % of total

$\bar{\nu}_\mu$ - NuMI neutrino mode run

$\bar{\nu}_\mu$ statistics is very low in neutrino-mode run

$(1p/0p)_{FLUKA}=0.35$

Data-MC comparison

μ^-/μ^+(DATA)=0.36

μ^-/μ^+(MC)=0.36

$\bar{\nu}_\mu$ - anti-neutrino mode

Multiplicity	Genie	Genie % of Total	DATA	DATA % of Total
0p+1mu	553±11	60%	422±42	58%
1p+1mu	160±6	17%	266±53	37%
2p+1mu	68±4	7%	30±6	4%
3p+1mu	50±3	5%	3±1	0.4%
4p+1mu	32±3	4%	3±1	0.4%
TOTAL (including >4p)	925±15	-	727±68	-

data 21% lower

ν_μ - anti-neutrino mode run

Multiplicity	Genie	Genie % of Total	DATA	DATA % of Total
0p+1mu	46±3	14%	60±12	23%
1p+1mu	163±6	48%	154±31	59%
2p+1mu	46±3	13.6%	33±7	13%
3p+1mu	23±2	7%	9±2	3.5%
4p+1mu	16±2	5%	4±1	1.5%
TOTAL (including >4p)	337±9	-	260±34	-

data 23% lower

Data-MC comparison

μ^-/μ^+(DATA)=0.36

μ^-/μ^+(MC)=0.36

$\bar{\nu}_\mu$ - anti-neutrino mode

Multiplicity	Genie	Genie % of Total	DATA	DATA % of Total
0p+1mu	553±11	60%	422±42	58%
1p+1mu	160±6	17%	266±53	37%
2p+1mu	68±4	7%	30±6	4%
3p+1mu	50±3	5%	3±1	0.4%
4p+1mu	32±3	4%	3±1	0.4%
TOTAL (including >4p)	925±15	-	727±68	-

← this is closest to MiniBooNE selection (muon and any # nucleons)

← this is closest to MINERvA $\bar{\nu}$ QE selection

ν_μ - anti-neutrino mode run

Multiplicity	Genie	Genie % of Total	DATA	DATA % of Total
0p+1mu	46±3	14%	60±12	23%
1p+1mu	163±6	48%	154±31	59%
2p+1mu	46±3	13.6%	33±7	13%
3p+1mu	23±2	7%	9±2	3.5%
4p+1mu	16±2	5%	4±1	1.5%
TOTAL (including >4p)	337±9	-	260±34	-

} ← this is closest to NOMAD and SciBooNE selection (1+2 track QE)

← this is closest to MiniBooNE selection (muon and any # nucleons)

ARGONEUT DATA-MC COMPARISON (I)

Lots of infos
not yet processed, e.g.
μ^-/μ^+(DATA)=0.36
μ^-/μ^+(MC)=0.36

$\bar{\nu}_\mu$ - anti-neutrino mode run (μ^+)

Multiplicity	Genie	Genie % of Total	DATA	DATA % of Total	DATA/MC RATIO
0p+1mu	553±11	60%	422±42	58%	0.76
1p+1mu	160±6	17%	266±53	37%	1.66
2p+1mu	68±4	7%	30±6	4%	0.44
3p+1mu	50±3	5%	3±1	0.4%	0.06
4p+1mu	32±3	4%	3±1	0.4%	0.09
TOTAL (including >4p	925±15	-	727±68	-	0.79

$(1p/0p)_{DATA}=0.63$
$(1p/0p)_{MC}=0.29$

0p events:
$(\mu^+/\mu^-)_{DATA}=7$
$(\mu^+/\mu^-)_{MC}=12$

ν_μ - anti-neutrino mode run (μ^-)

Multiplicity	Genie	Genie % of Total	DATA	DATA % of Total	DATA/MC RATIO
0p+1mu	46±3	14%	60±12	23%	1.3
1p+1mu	163±6	48%	154±31	59%	0.94
2p+1mu	46±3	13.6%	33±7	13%	0.71
3p+1mu	23±2	7%	9±2	3.5%	0.39
4p+1mu	16±2	5%	4±1	1.5%	0.25
TOTAL (including >4p	337±9	-	260±34	-	0.77

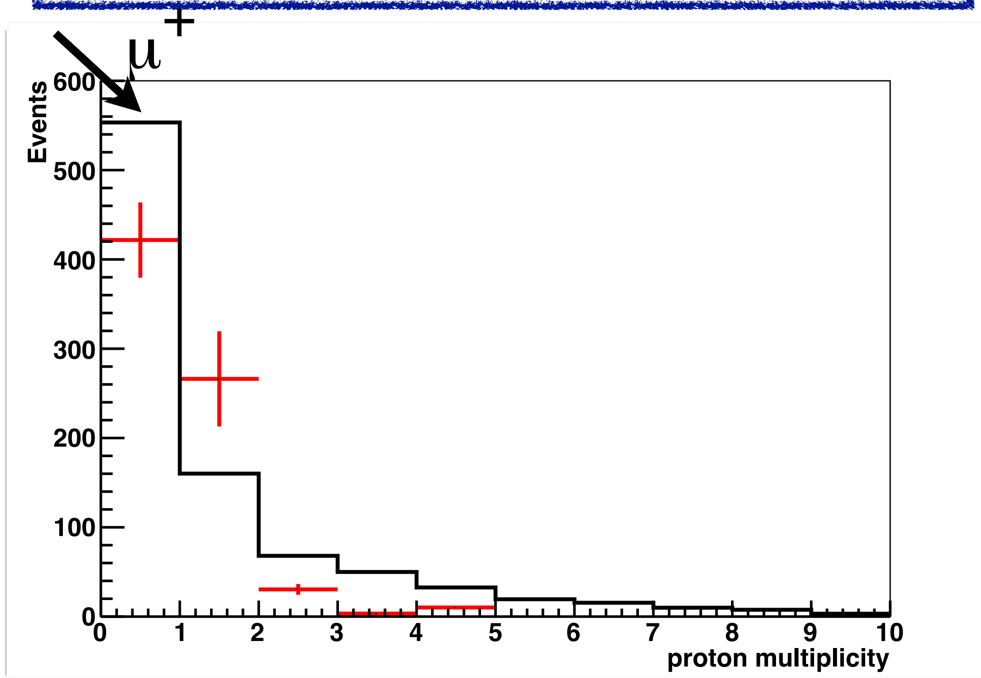
$(0p/1p)_{DATA}=0.39$
$(0p/1p)_{MC}=0.28$

- $\frac{N_{\mu-}}{N_{\mu+}}$ ratio

0p events
Useful for FSI studies: indication of nucleon charge exchange in Ar nuclei, less dependent (at 1st order) on multinucleon production

ARGONEUT DATA-MC COMPARISON (II)

$\bar{\nu}_\mu$ - anti-neutrino mode run



ArgoneuT data 727±68

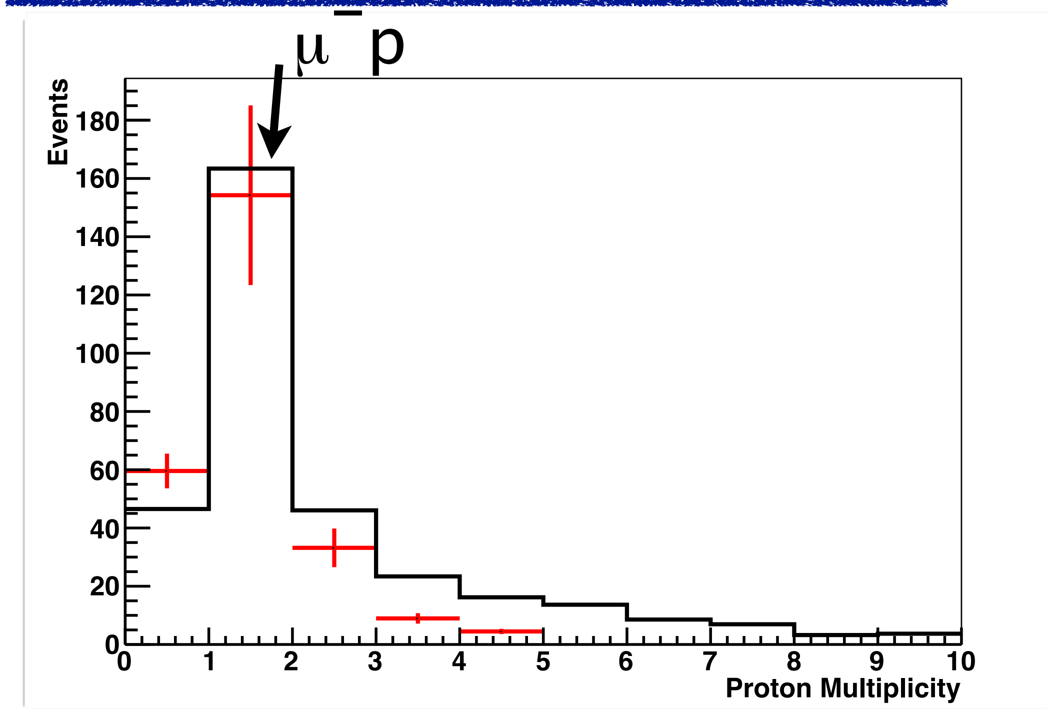
Genie 925±15

Genie: 626 CCQE events

(+ 33% contribution from not CCQE)

NUANCE: 636 CCQE events

ν_μ - anti-neutrino mode run



ArgoneuT data 260±34

Genie 337±9

Genie: 230 CCQE events

(+ 32% contribution from not CCQE)

NUANCE: 230 CCQE events

- Ratios among rates of different proton multiplicities in DATA don't agree with MC, in particular for $\bar{\nu}_\mu$
- MC agreement on total number of CCQE events
- Large (~30%) contribution from not CCQE events (FSI)

Started reconstruction of protons and looking at their kinematics
(on subsample, analysis in progress)

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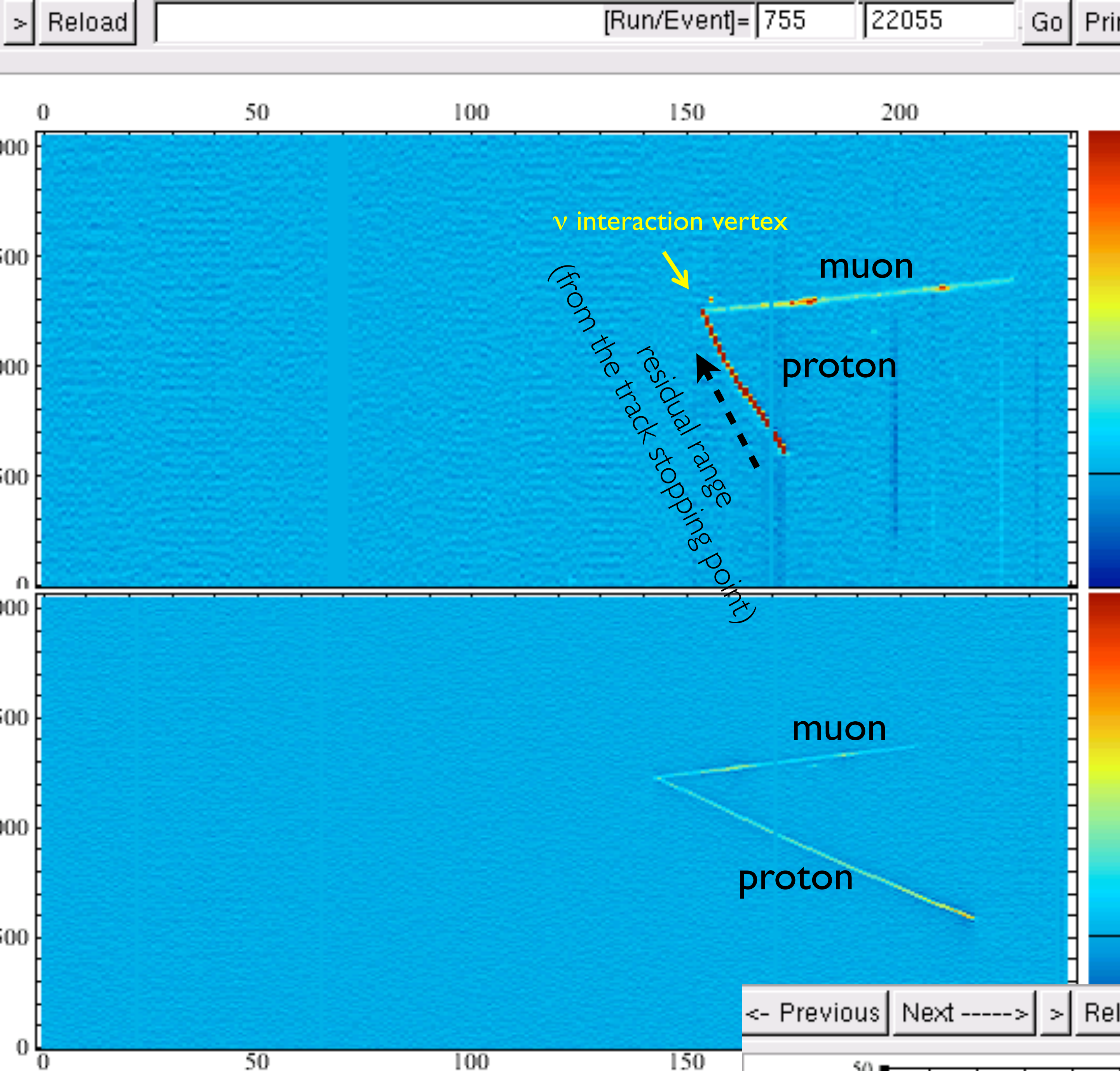
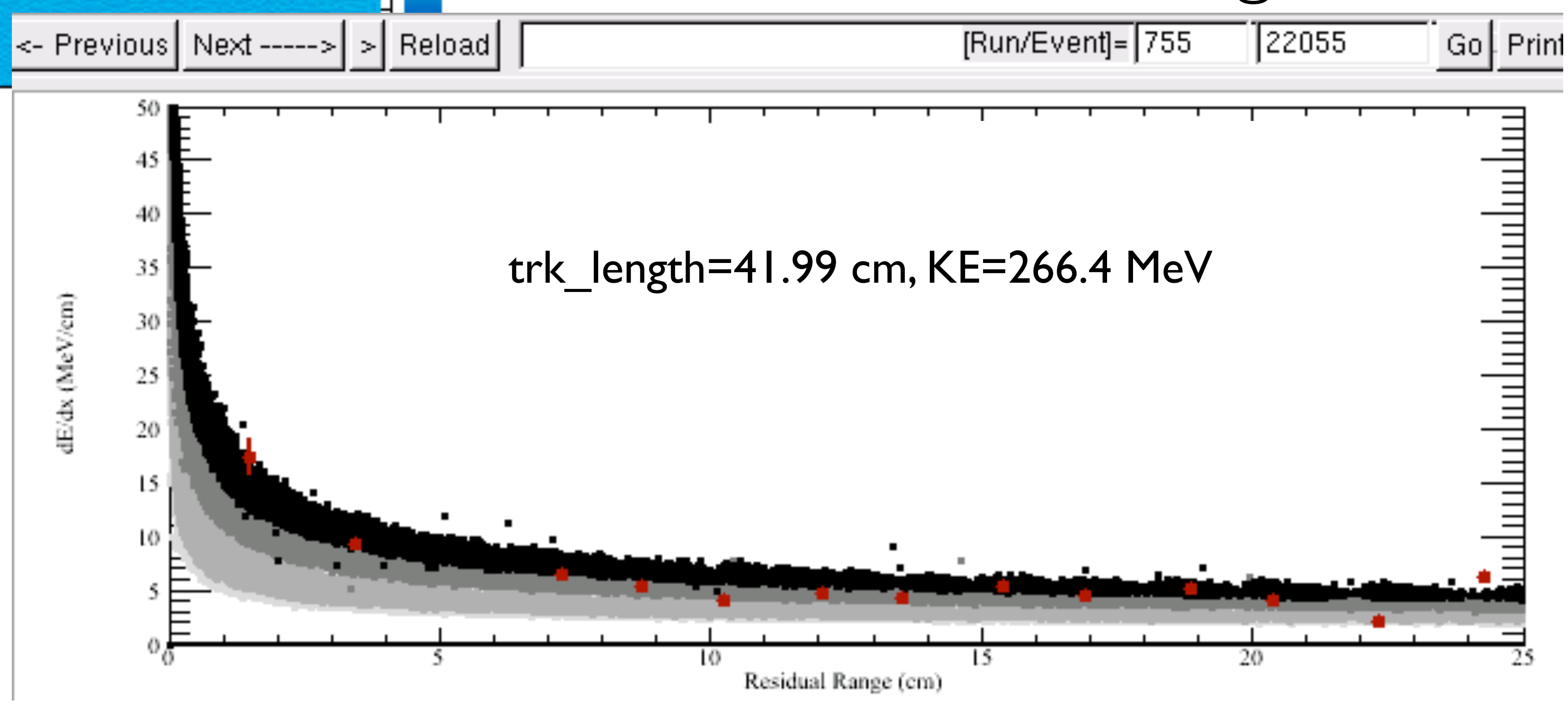
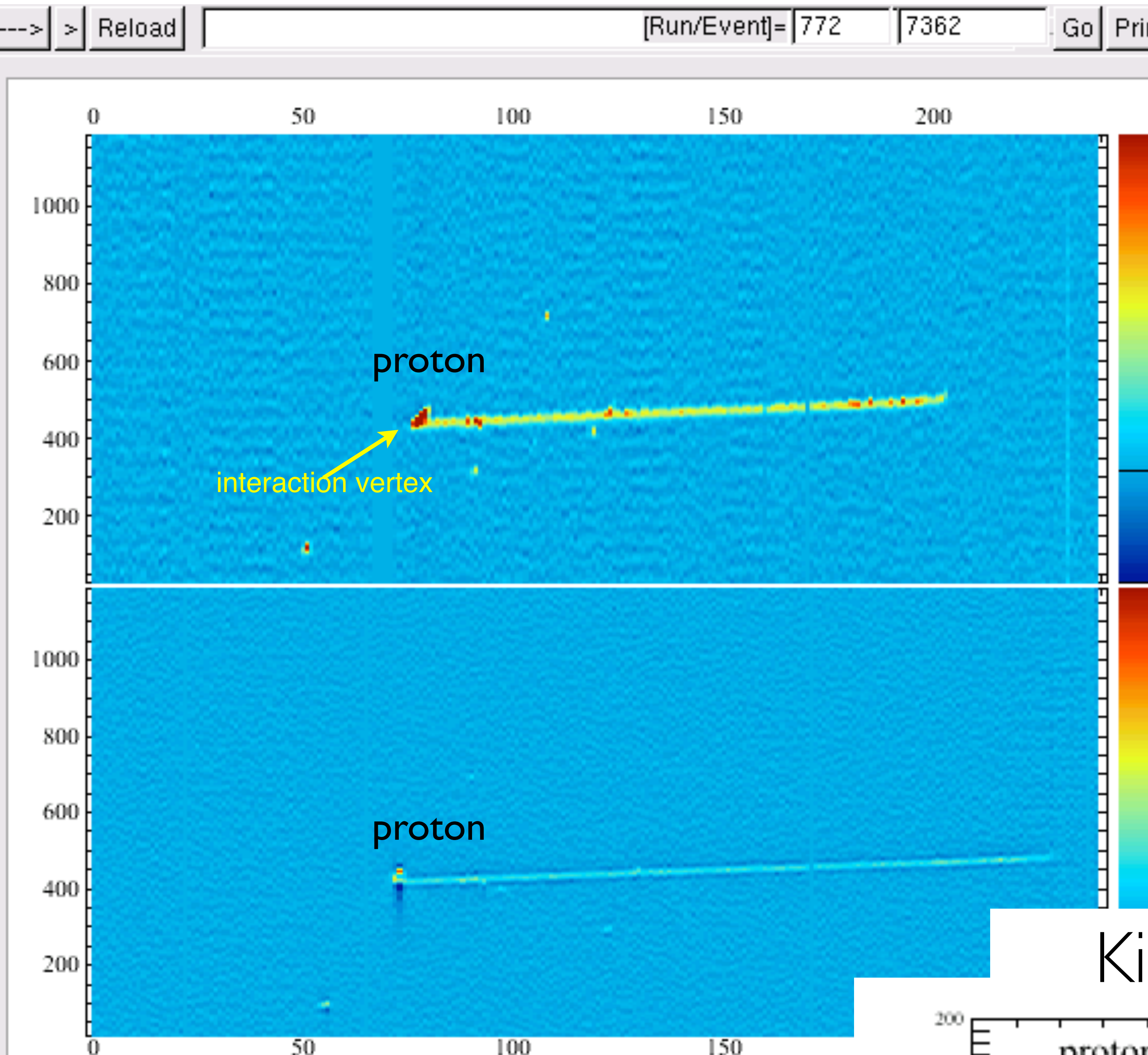


dE/dx vs. residual range

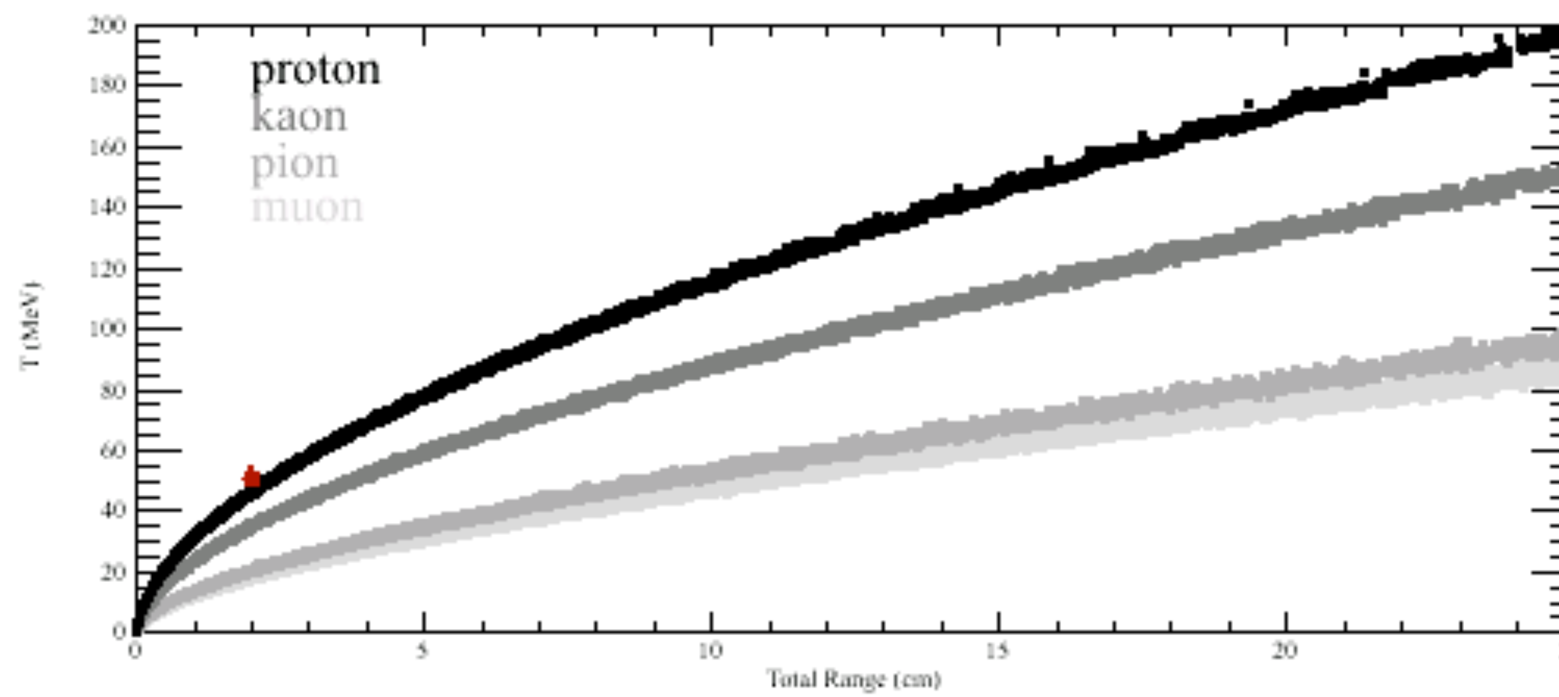


Low energy proton reconstruction



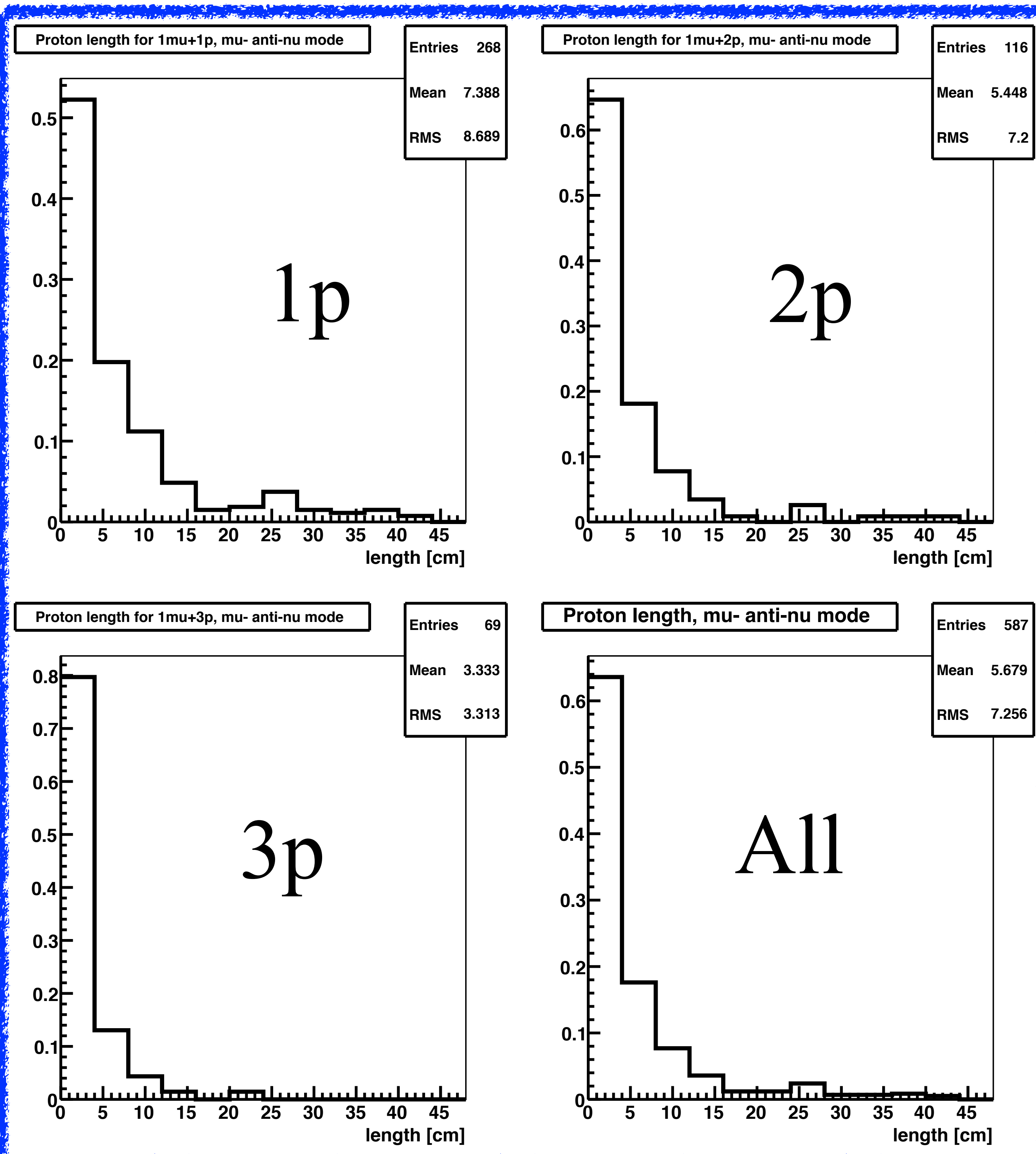
trk_length=1.99 cm, KE=46.55 MeV

Kinetic energy vs. track length

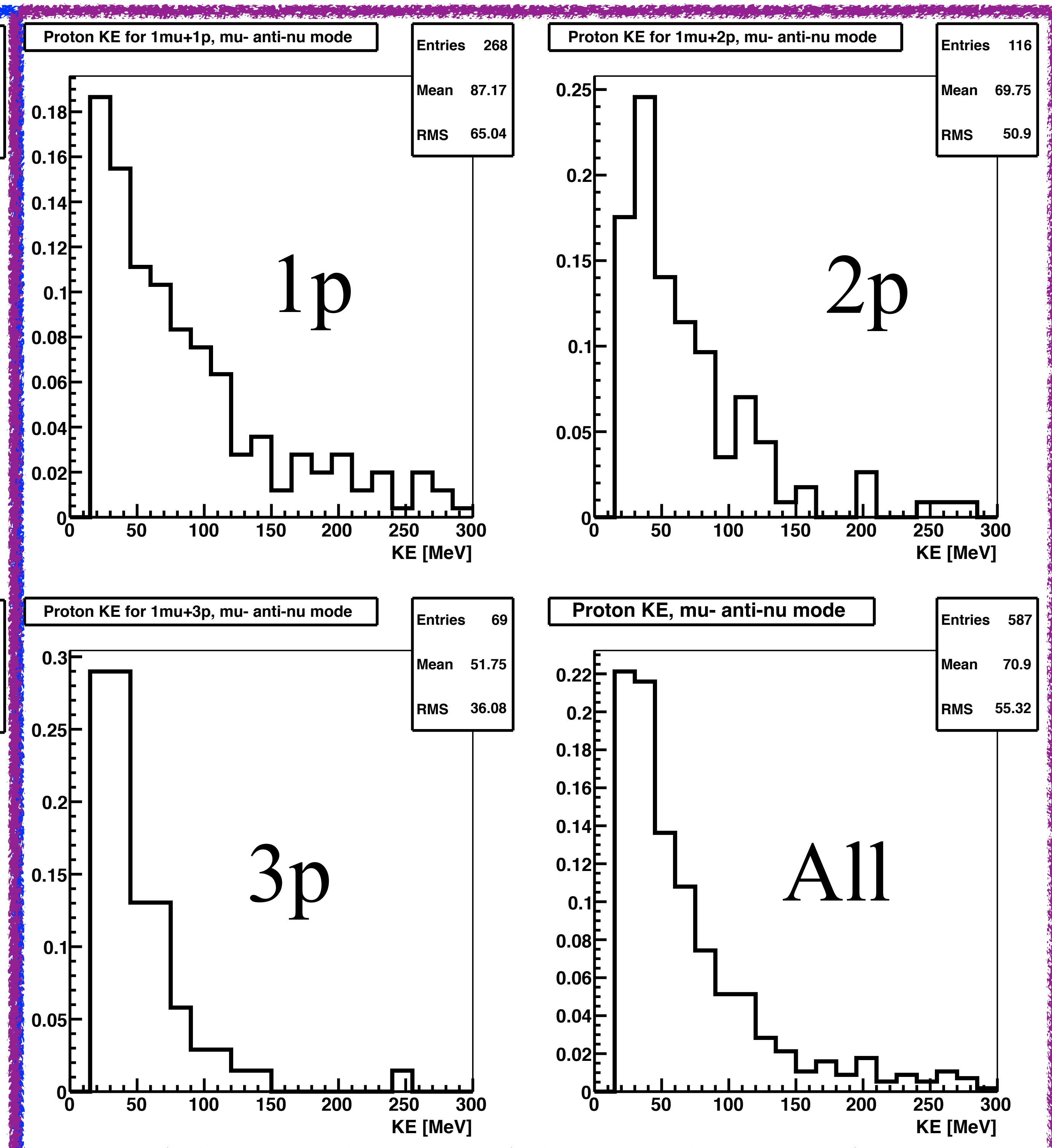


Proton Length and Kinetic Energy from GENIE, nu in anti-nu mode

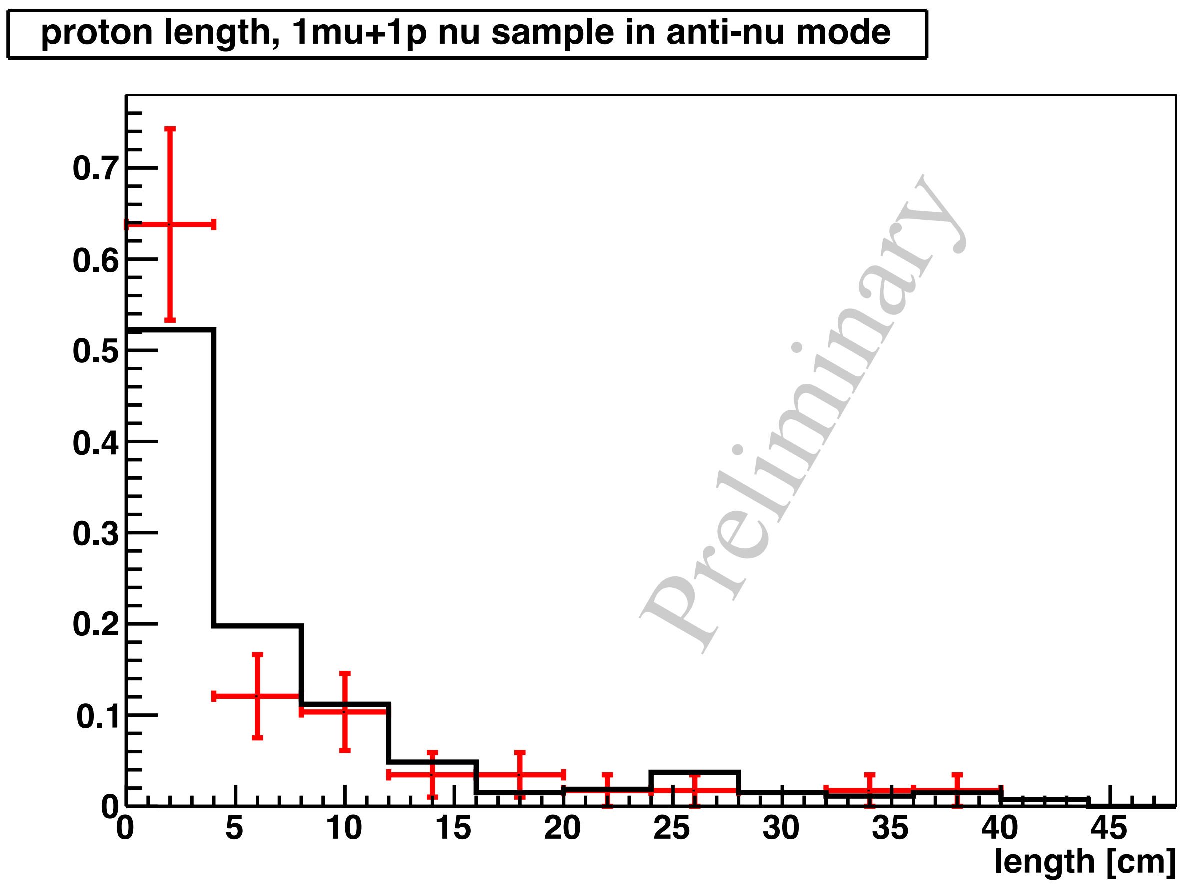
Length:

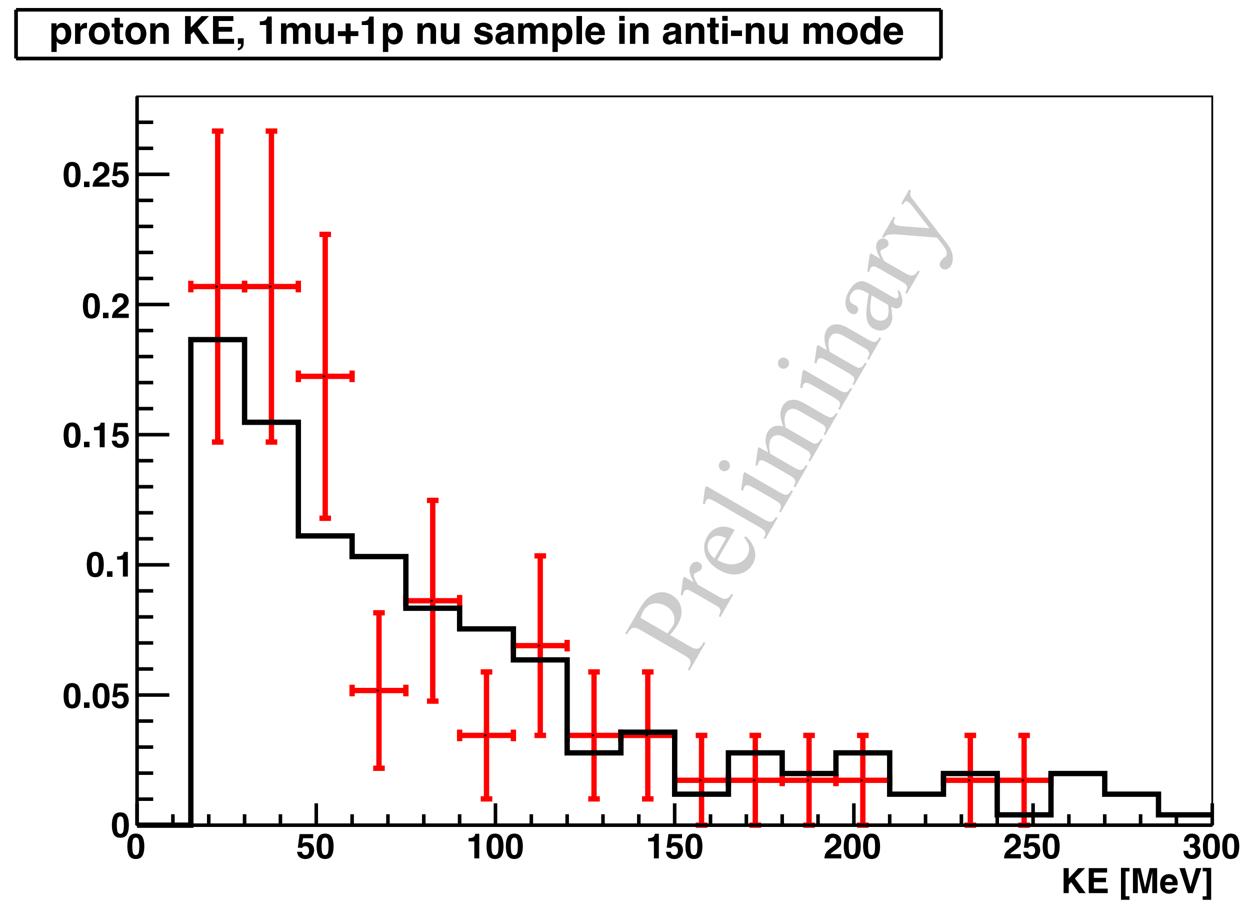


Kinetic Energy:



1μ+1p neutrino sample in anti-nu mode





DATA, mean: 6.2 cm

MC, mean: 7.4 cm

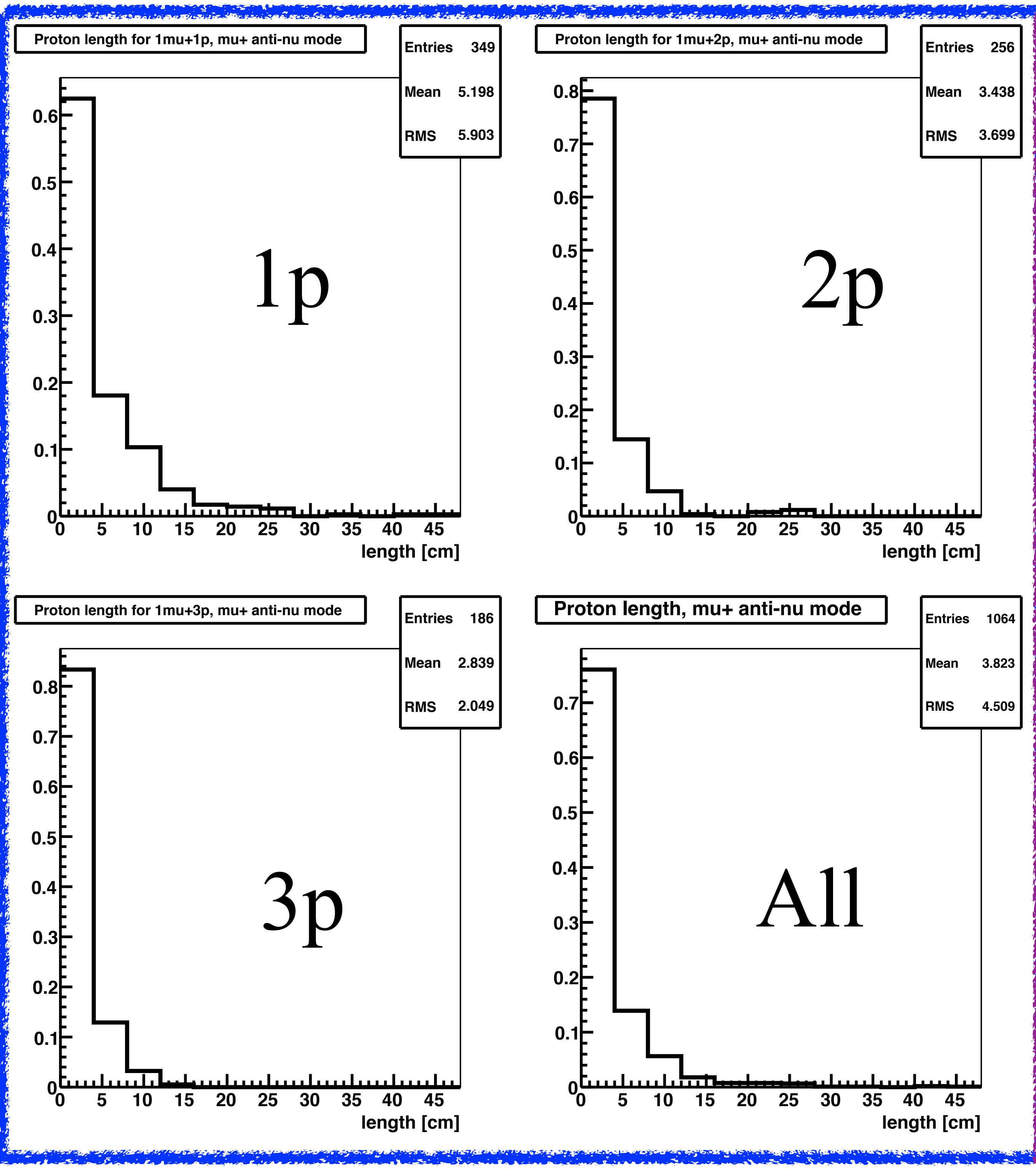
DATA, mean: 73.9 MeV

MC, mean: 87.2 MeV

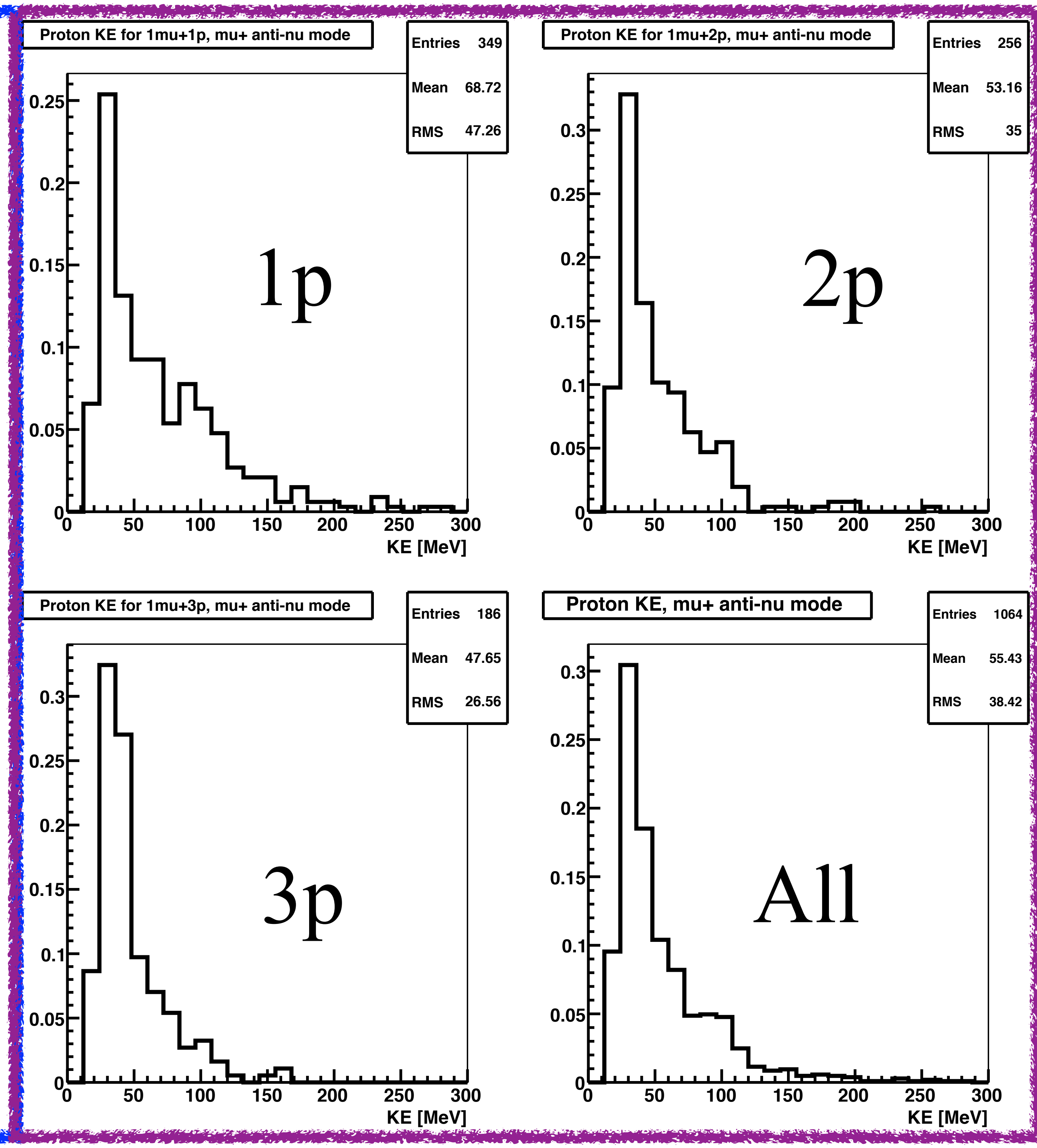
Area normalized, comparison inside detector with contained protons

Proton Length and Kinetic Energy from GENIE, anti-nu in anti-nu mode

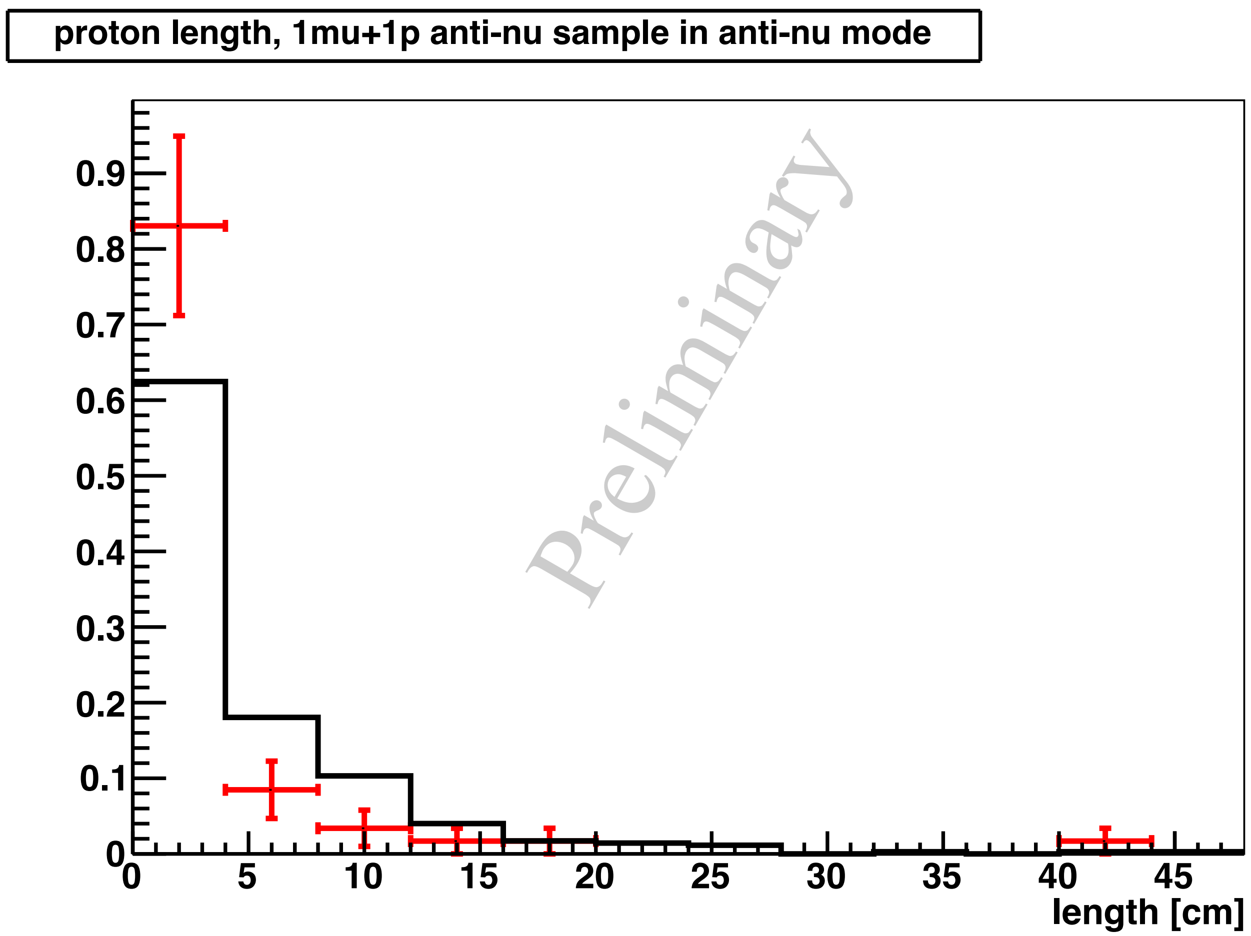
Length:

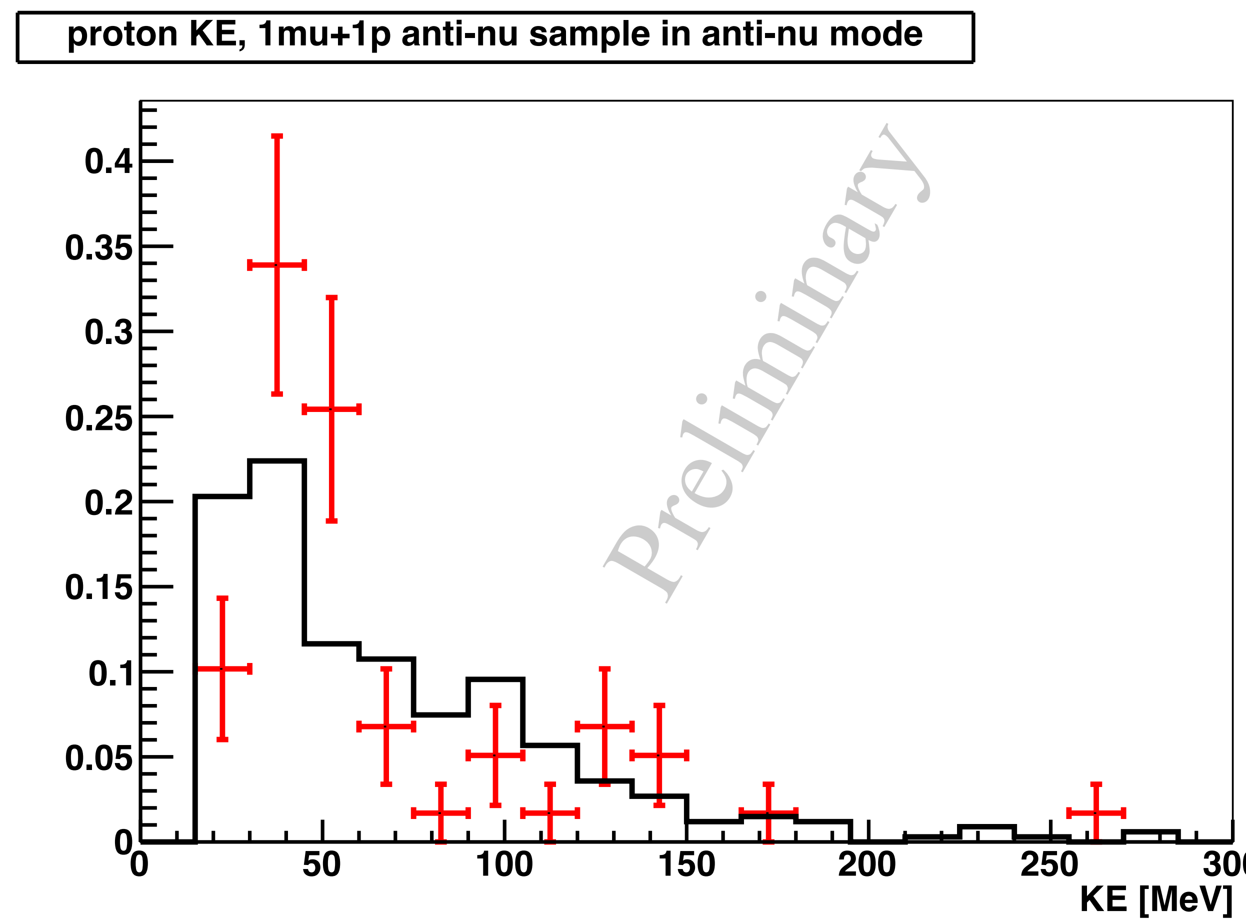


Kinetic Energy:



1μ+1p anti-neutrino sample in anti-nu mode





DATA, mean: 3.8 cm
MC, mean: 5.2 cm

DATA, mean: 63.5 MeV
MC, mean: 68.7 MeV

Area normalized, comparison inside detector with contained protons

Higher multiplicity comparisons in progress, also angular distributions

Neutrino Energy Reconstruction

$$E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos\theta_\mu)}$$

μ kinematics

automatic reconstruction

$$p_h = \sqrt{(E_\nu - p_\mu cos\theta_\mu)^2 + p_\mu^2 sin^2\theta_\mu}$$

$$cos\theta_h = (E_\nu - p_\mu cos\theta_\mu)/p_h$$

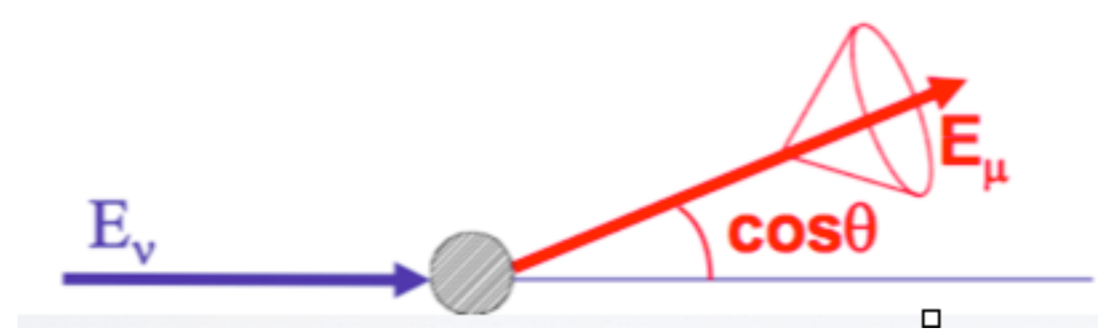
assumes QE events!

$$E_\nu = p_\mu \cos\theta_\mu + p_h \cos\theta_h$$

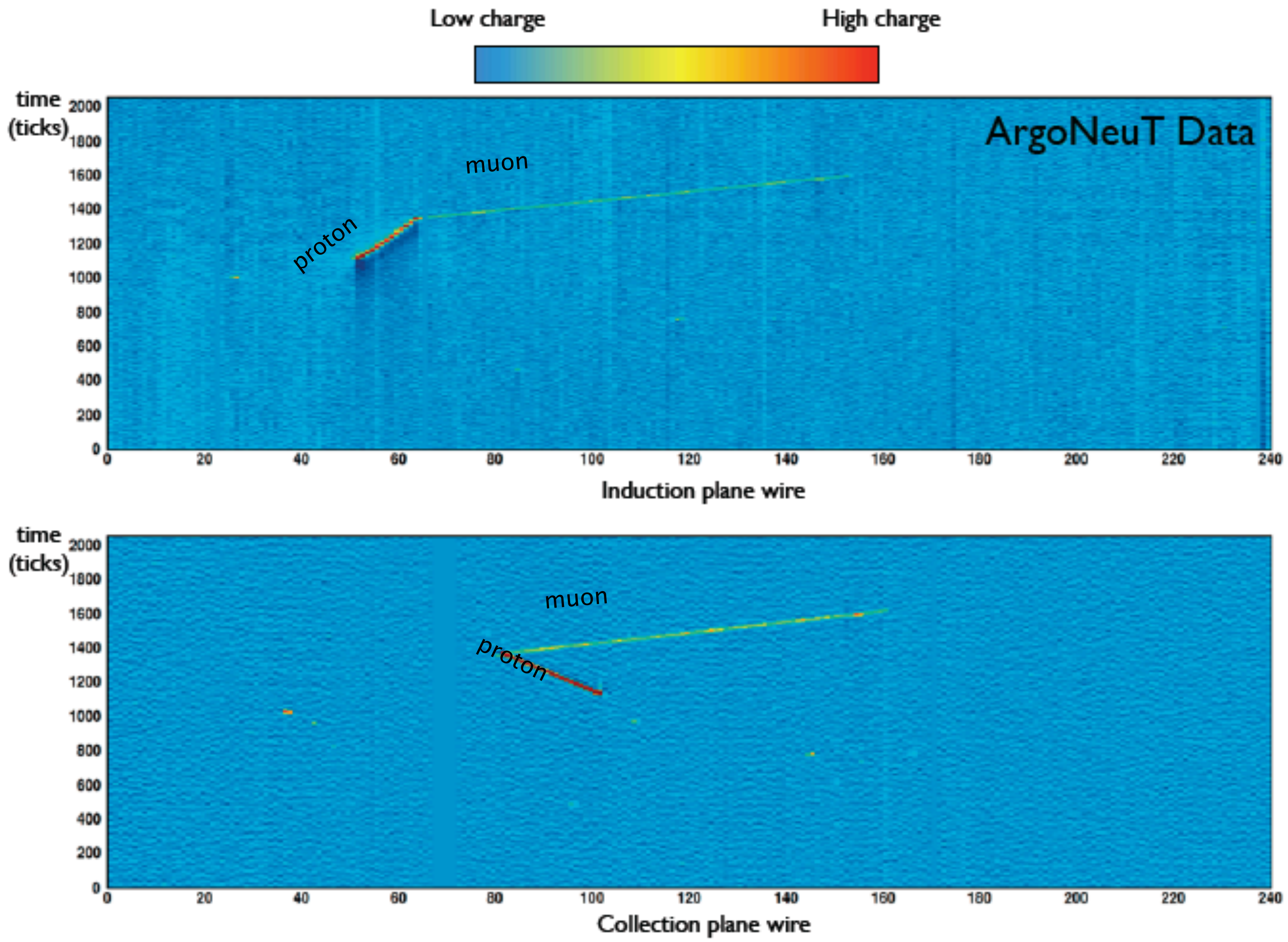
μ + p kinematics

semi-automatic reconstruction

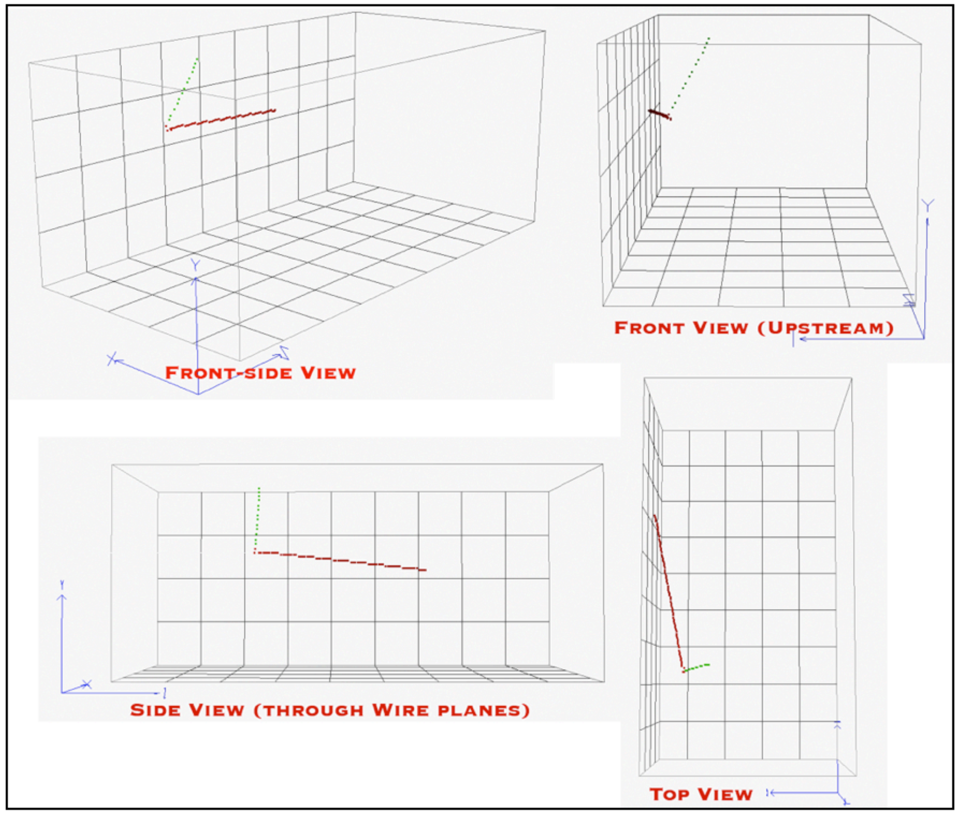
We can compare the two methods!



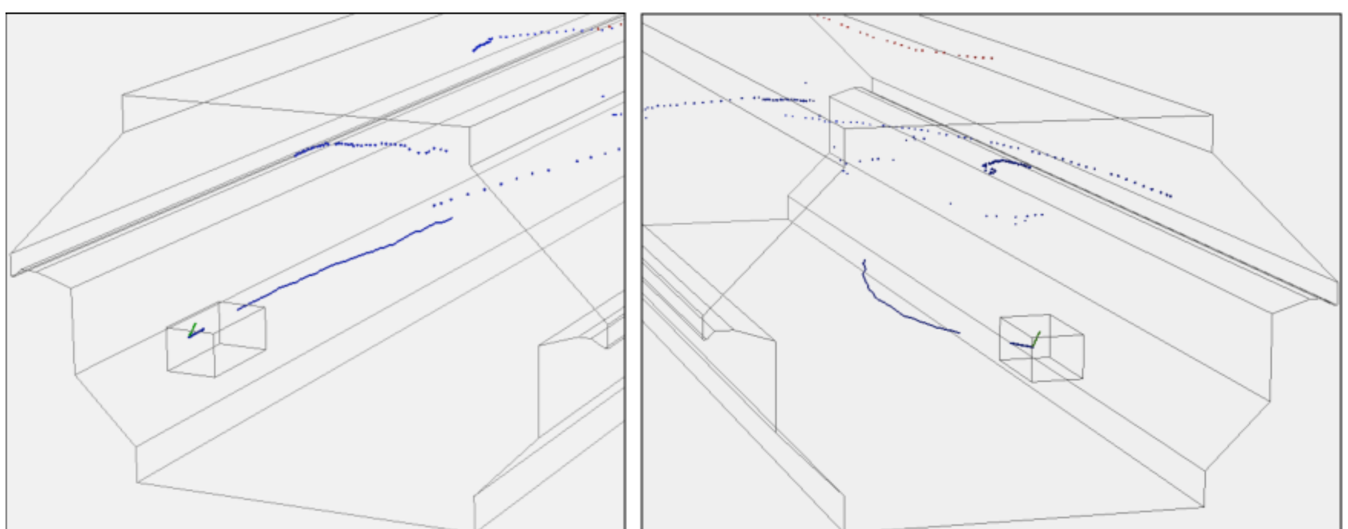
Reconstruction of $1\mu 1p$ events



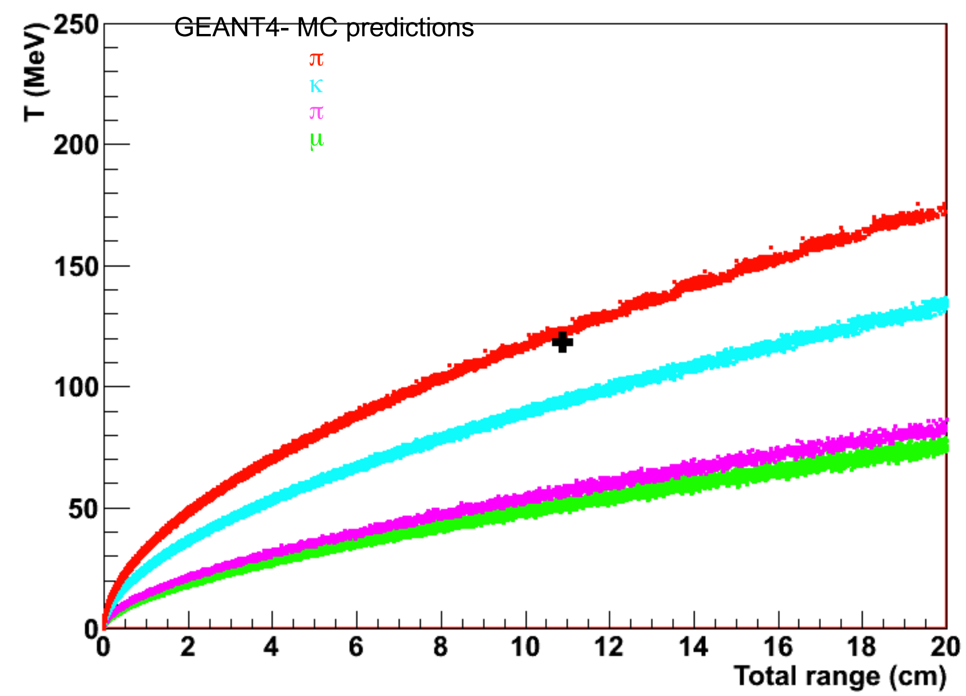
Neutrino event reconstructed in 3D space



μ– escaping ArgoNeuT (and reaching MINOS-ND downstream)



Full neutrino event reconstruction with 3D ArgoNeuT-MINOS ND track matching

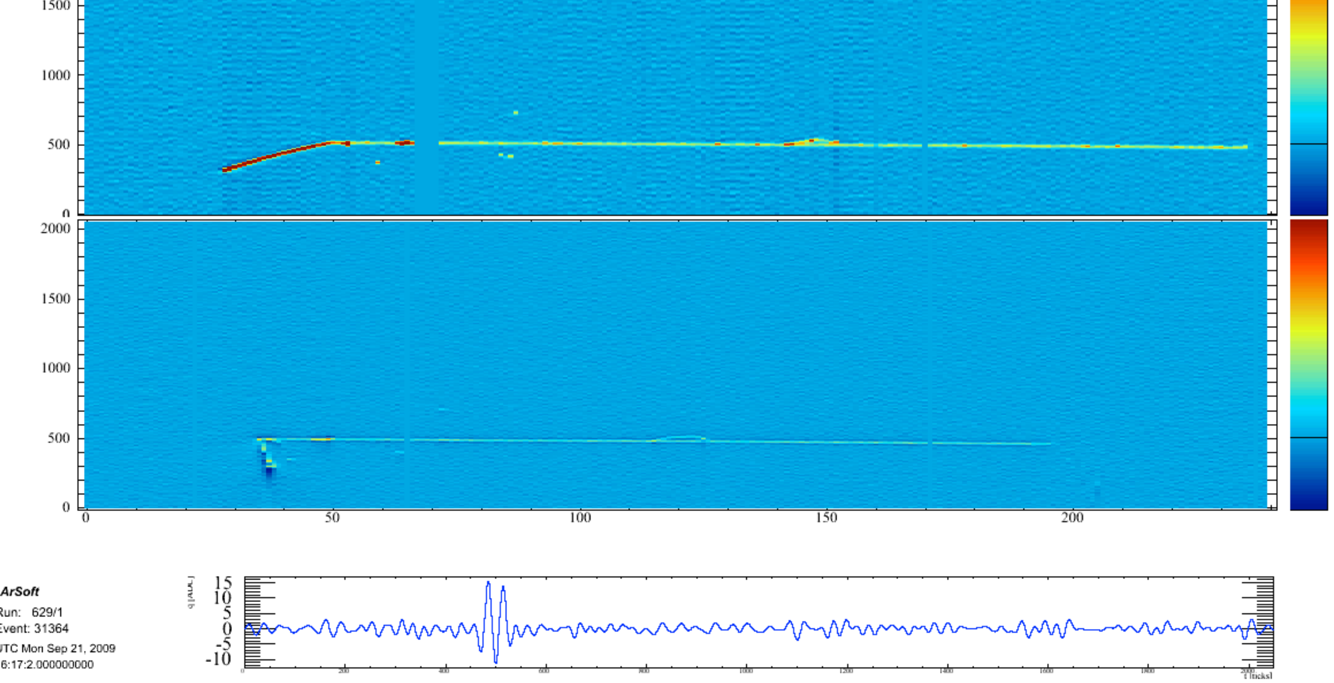


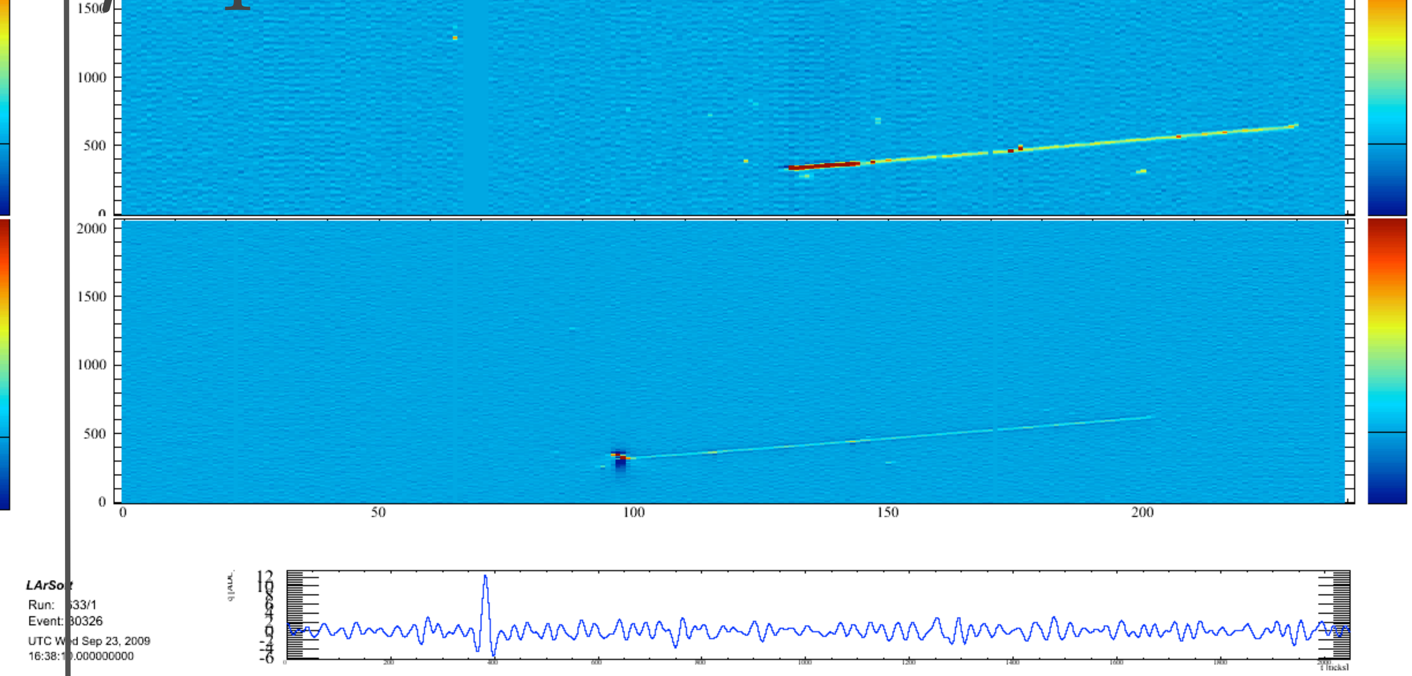
Proton (ArgoNeuT reconstruction):
track length= 10.88 cm,
T=118 MeV, p=0.485 GeV/c

$\mu + p$ kinematics — Reconstructed Neutrino Energy= 3.1 GeV

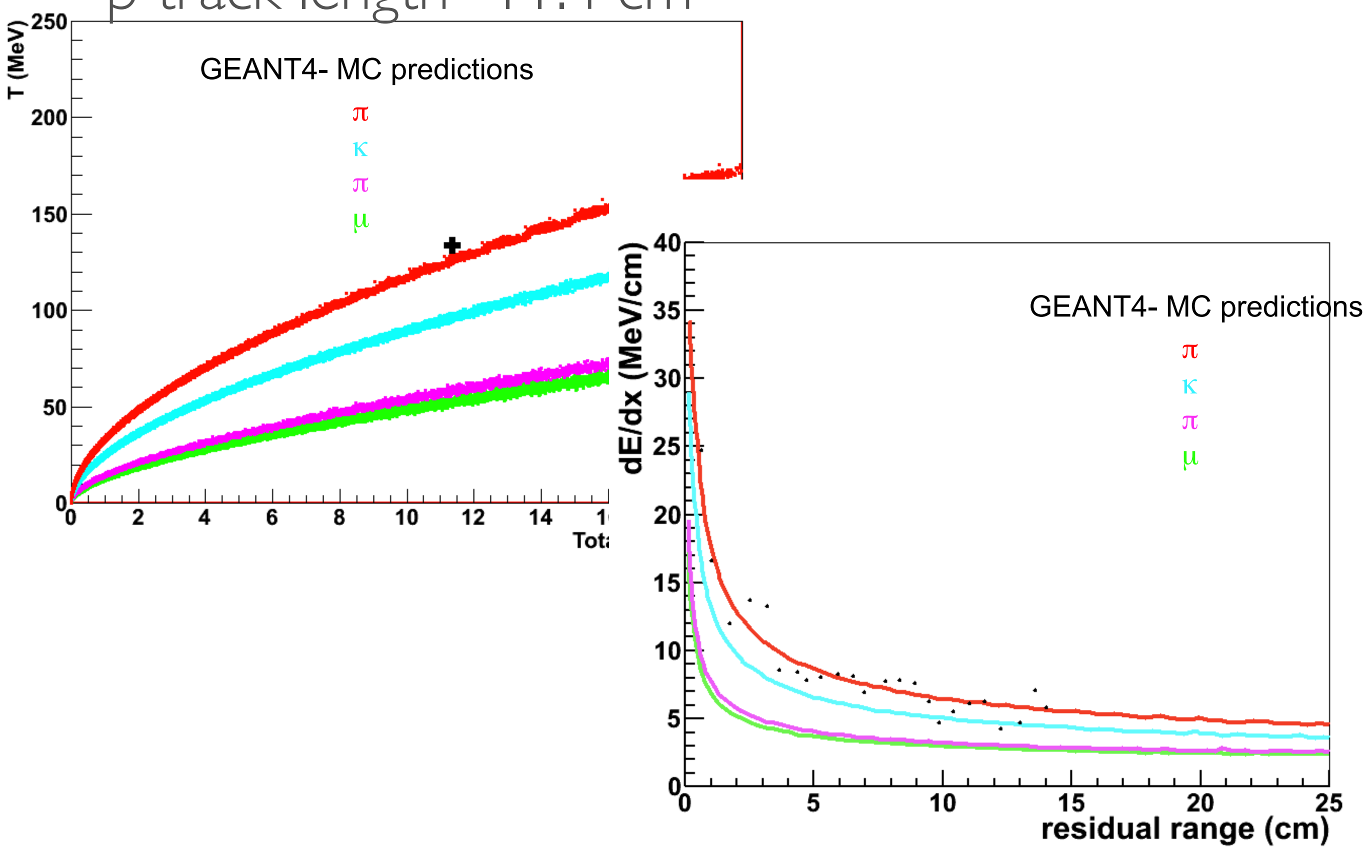
μ kinematics — Reconstructed Neutrino Energy= 3.0 GeV

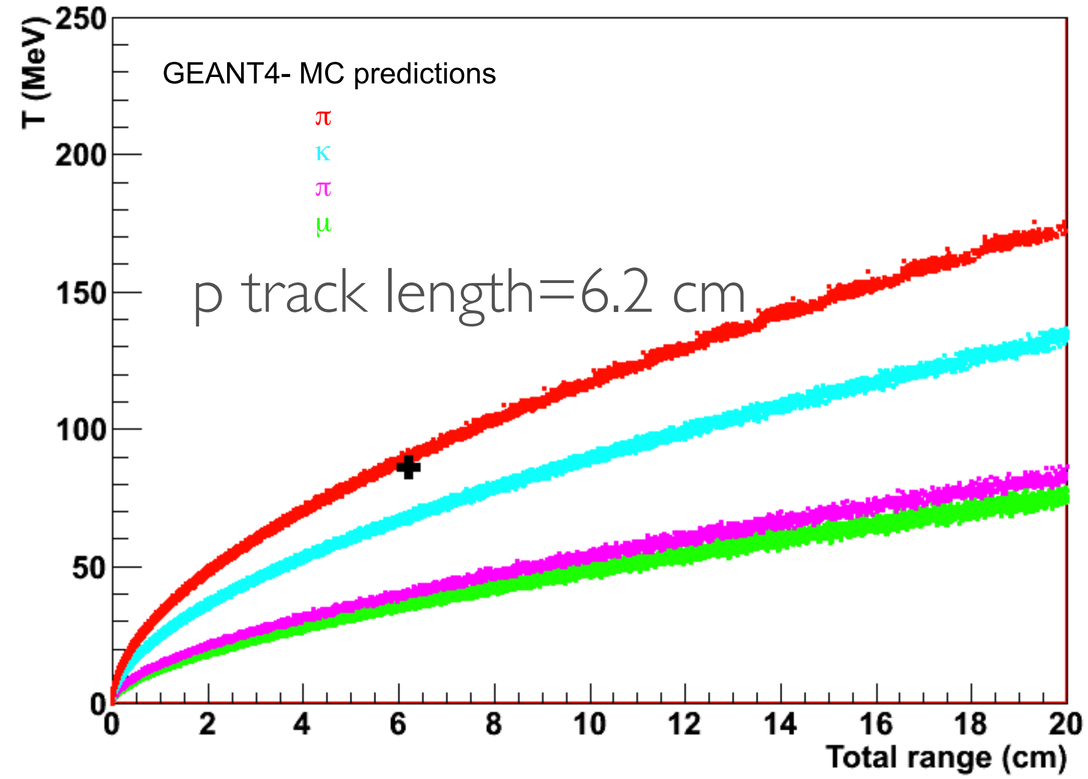
Reconstruction of 1μ1p events





p track length=11.4 cm





p track length=6.2 cm

μ+p kinematics	Reconstructed Neutrino Energy=3.3 GeV
μ kinematics	Reconstructed Neutrino Energy=3.3 GeV

μ+p kinematics	Reconstructed Neutrino Energy=6.5 GeV
μ kinematics	Reconstructed Neutrino Energy=6.0 GeV

Conclusions

- ArgoNeuT provides capability to identify and reconstruct exclusive topologies with low proton threshold (21 MeV)

- Enormous amount of information can be extracted, we are learning how to deal with each topology (e.g. multi-proton events)

- Proton multiplicity at the neutrino interaction vertex with presence of secondary particles in ArgoNeuT events and ratios among rates of different exclusive topologies provide indications on the size of nuclear effects in LAr, like FSI (and multi-nucleon production) in the few GeV energy region.

- The generators predict vastly varying amounts of proton emission. The ArgoNeuT data can provide an important discriminator among models. This is the first time we've had this type of data available to help guide us.

ArgoNeuT Collaboration

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The University of Texas at Austin

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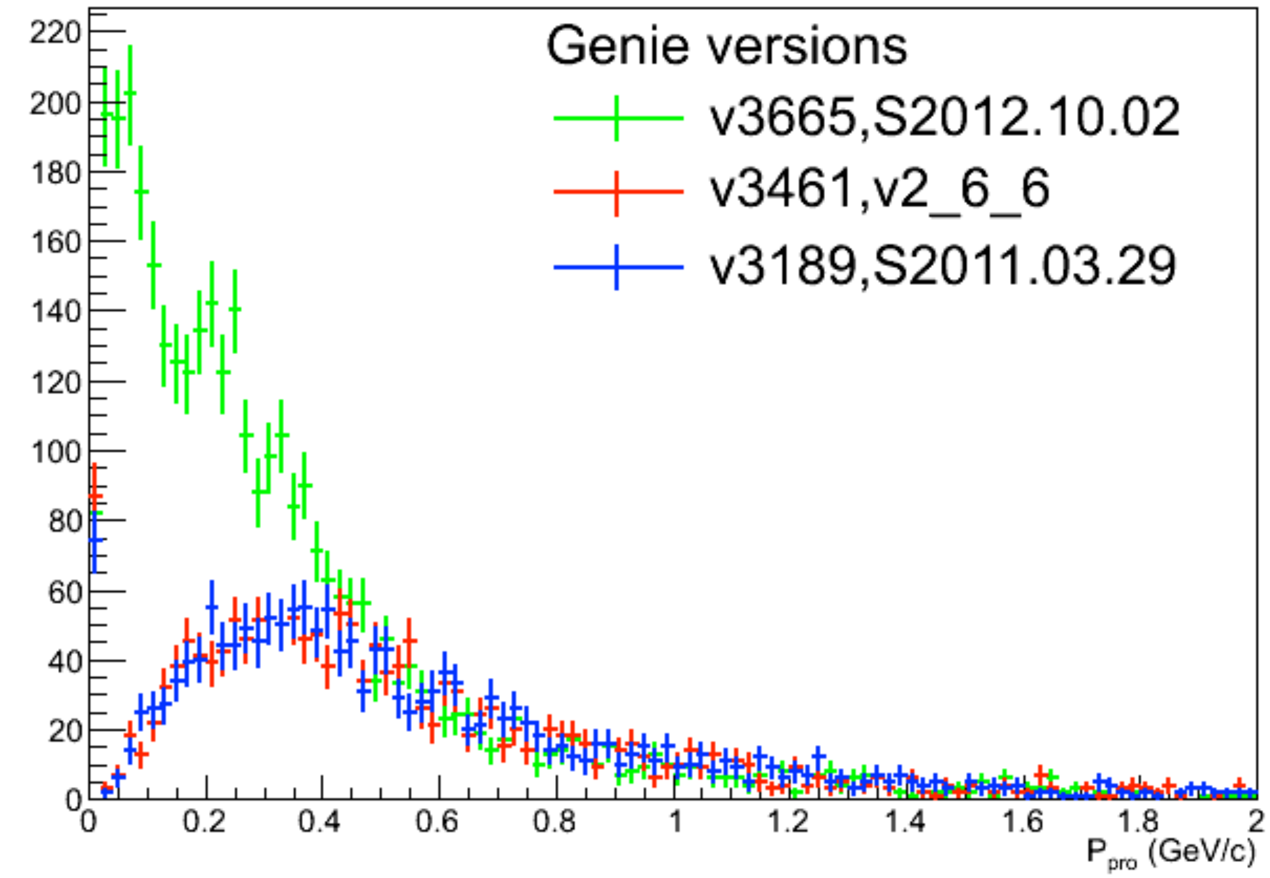
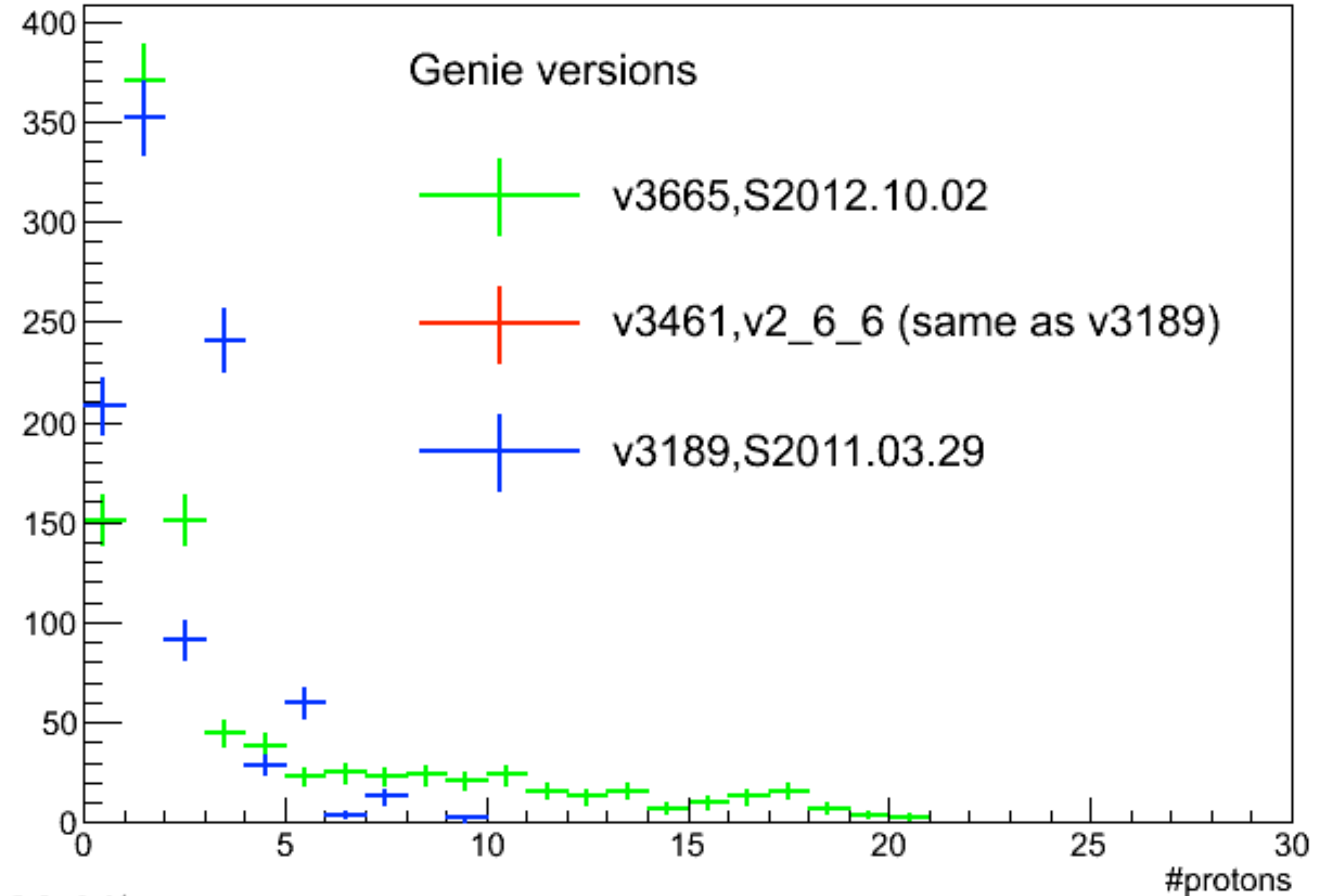
Yale University

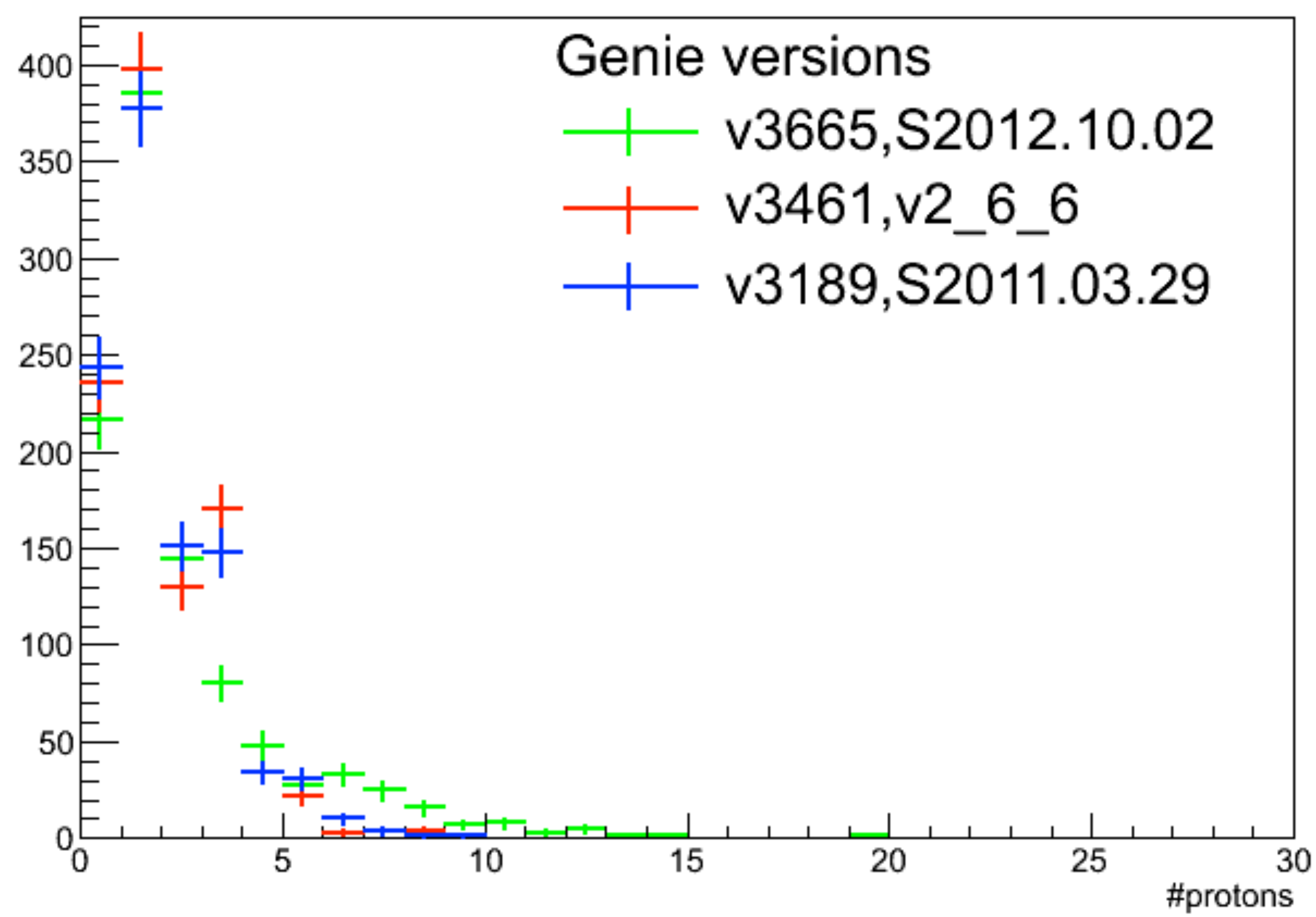
* spokesperson

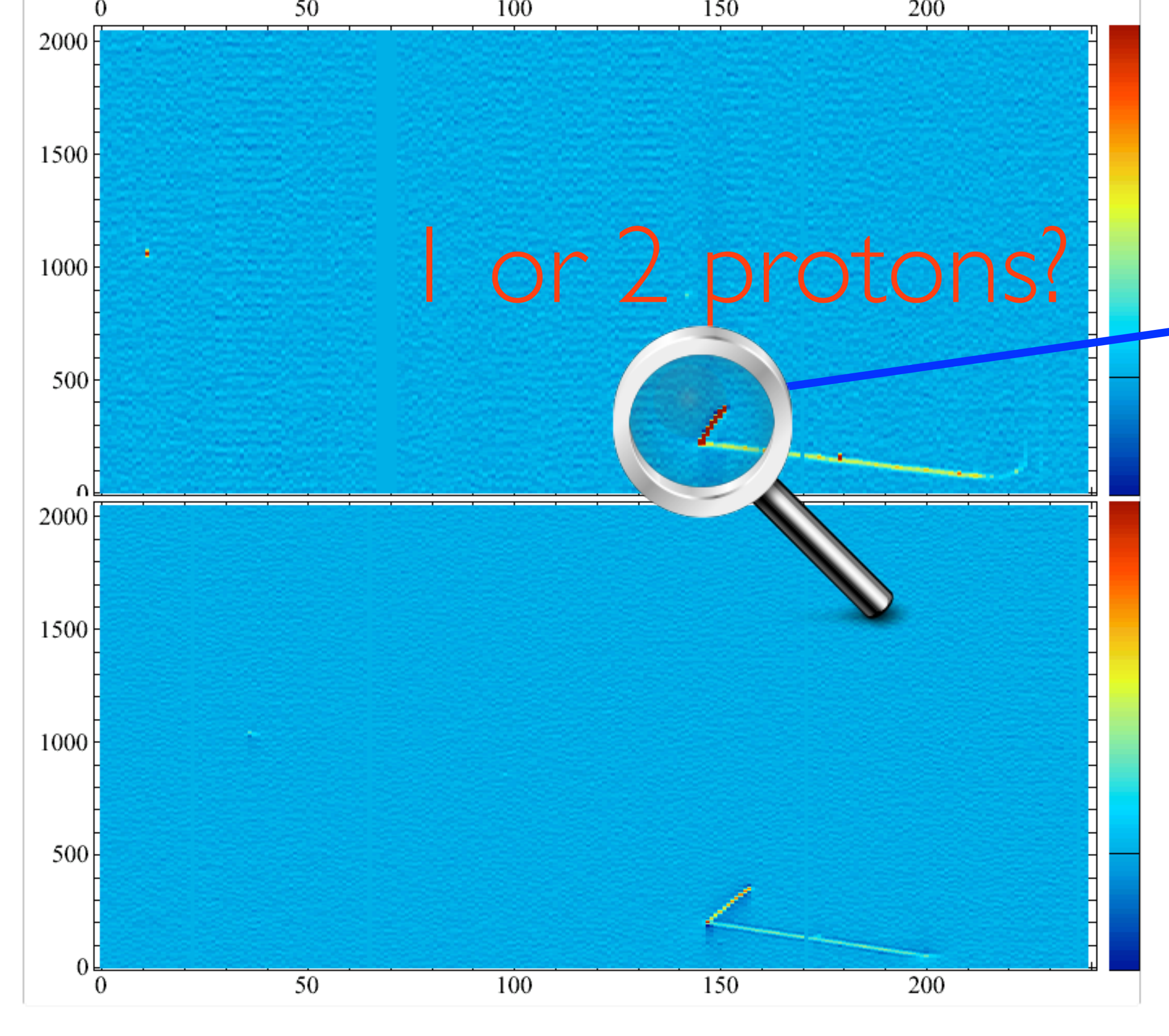
Back-up

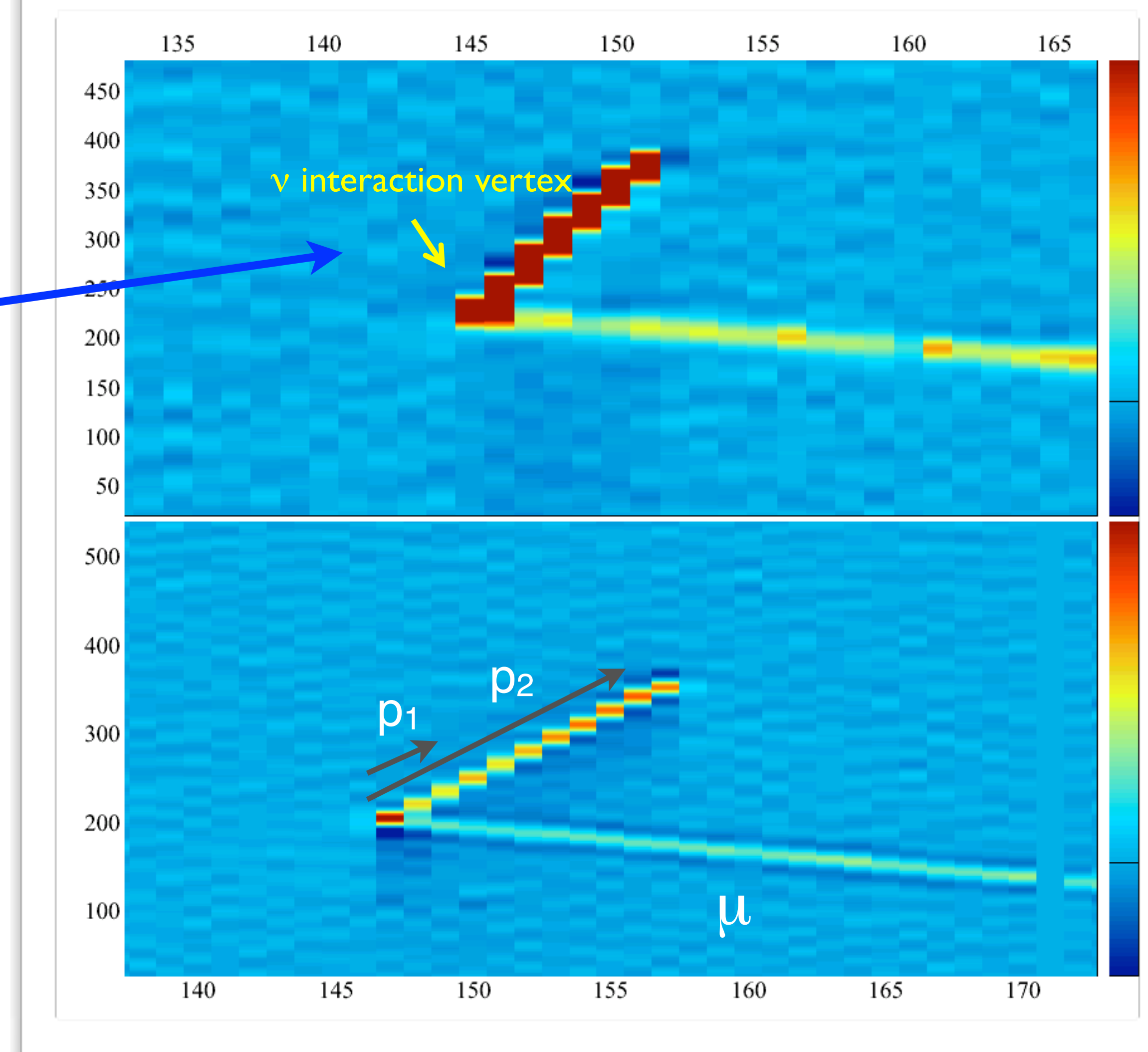

Genie versions
v3665,S2012.10.02
v3461,v2_6_6
v3189,S2011.03.29
P_pro (GeV/c)

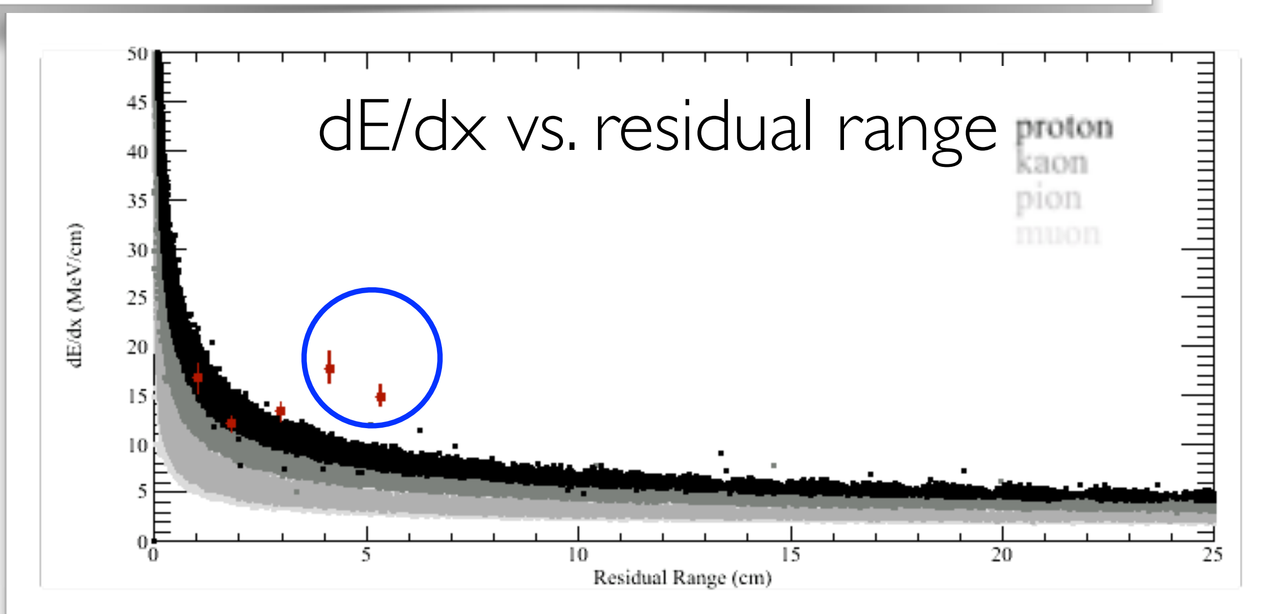

Genie versions
v3665,S2012.10.02
v3461,v2_6_6 (same as v3189)
v3189,S2011.03.29
#protons

P>200 MeV/c


Genie versions
v3665,S2012.10.02
v3461,v2_6_6
v3189,S2011.03.29
#protons

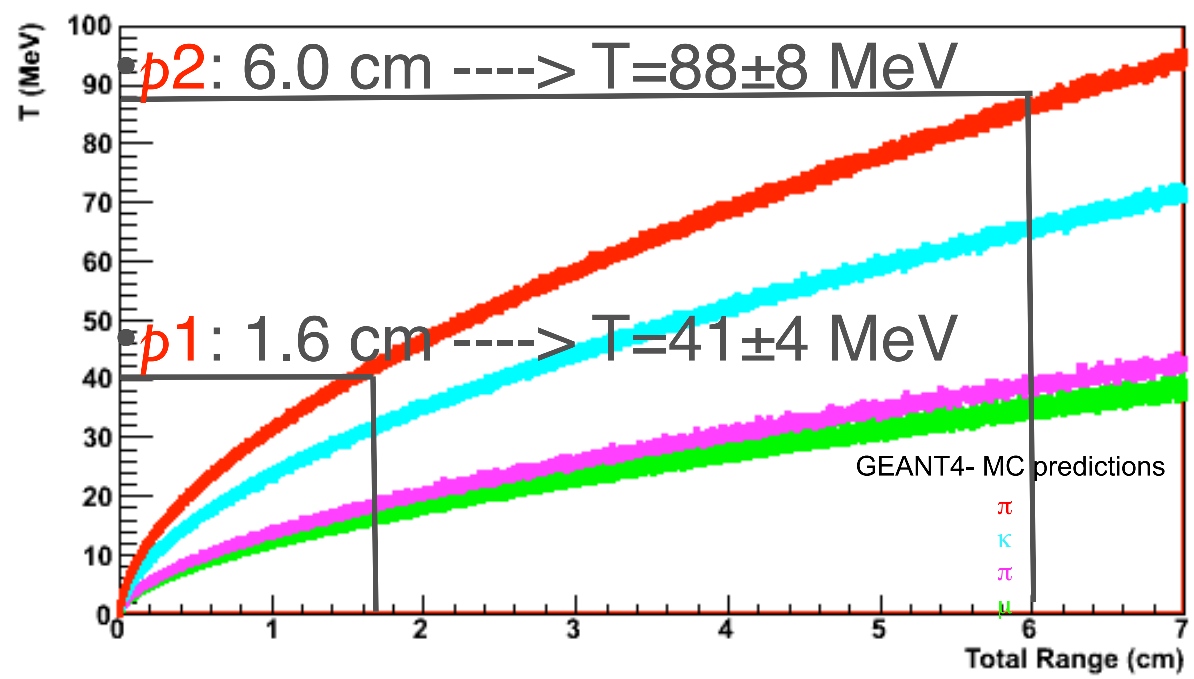




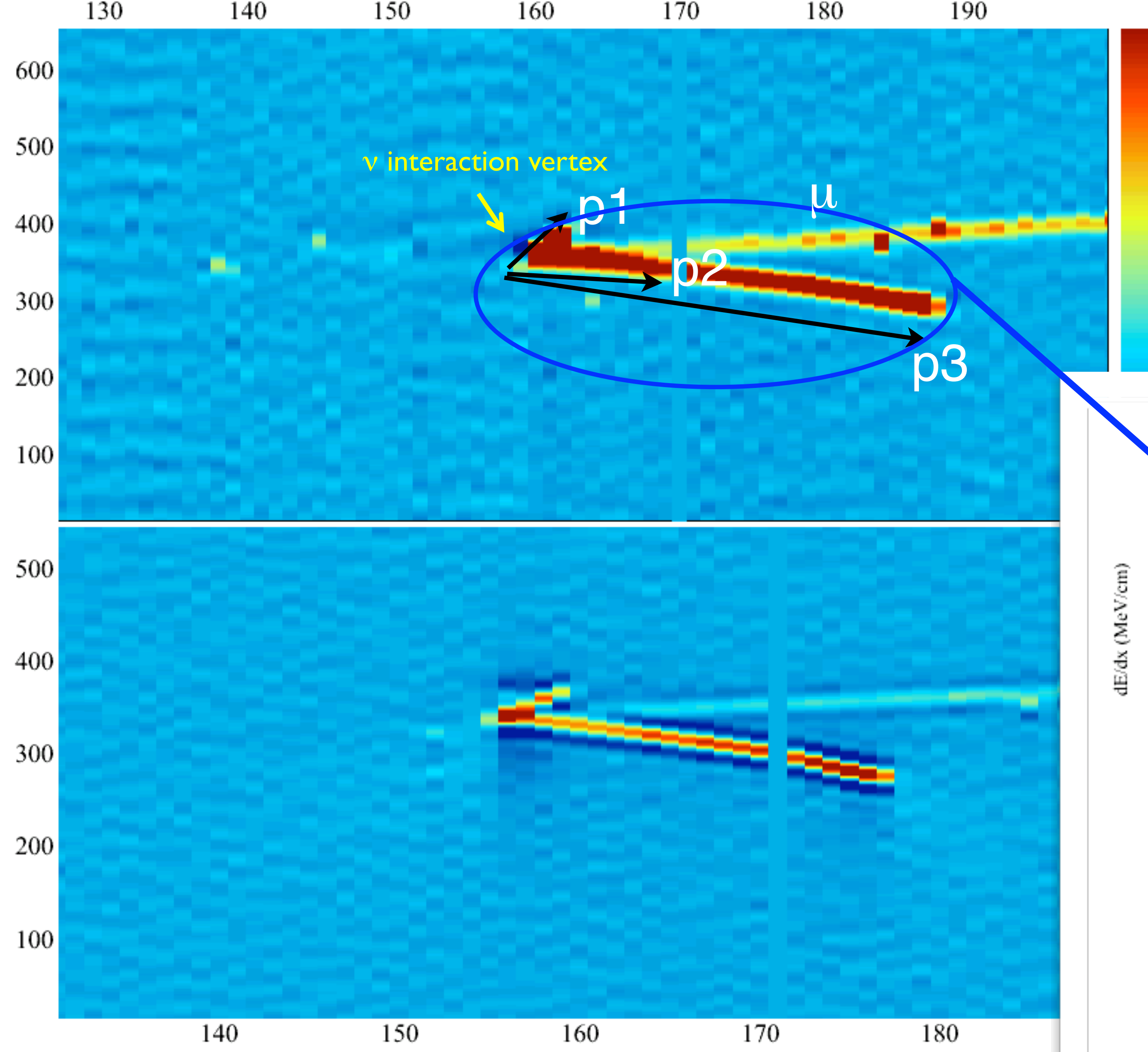


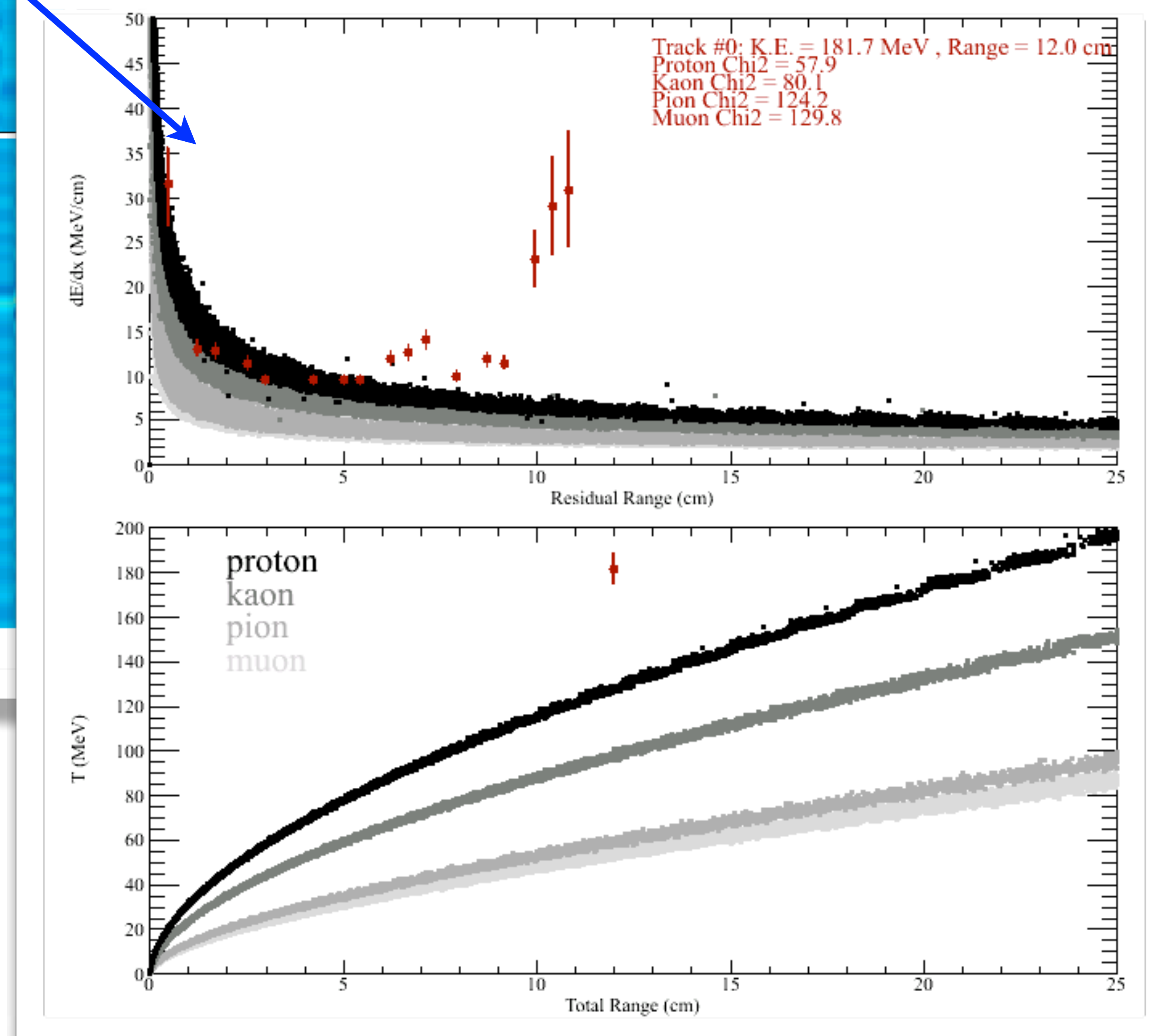
compatible with
1 μ 2p

17



DATA:
EXCLUSIVE TOPOLOGIES

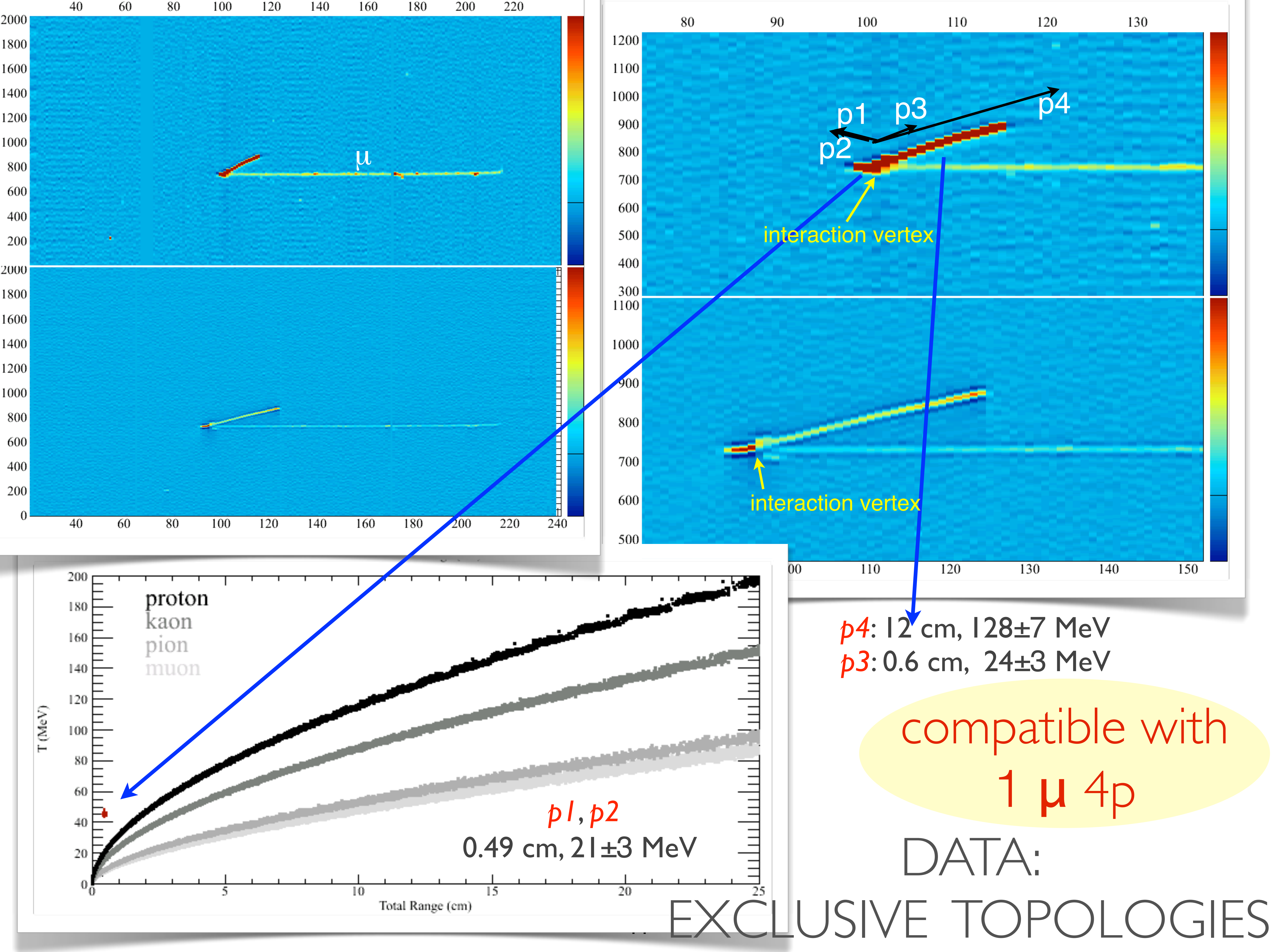




2 or 3 protons?

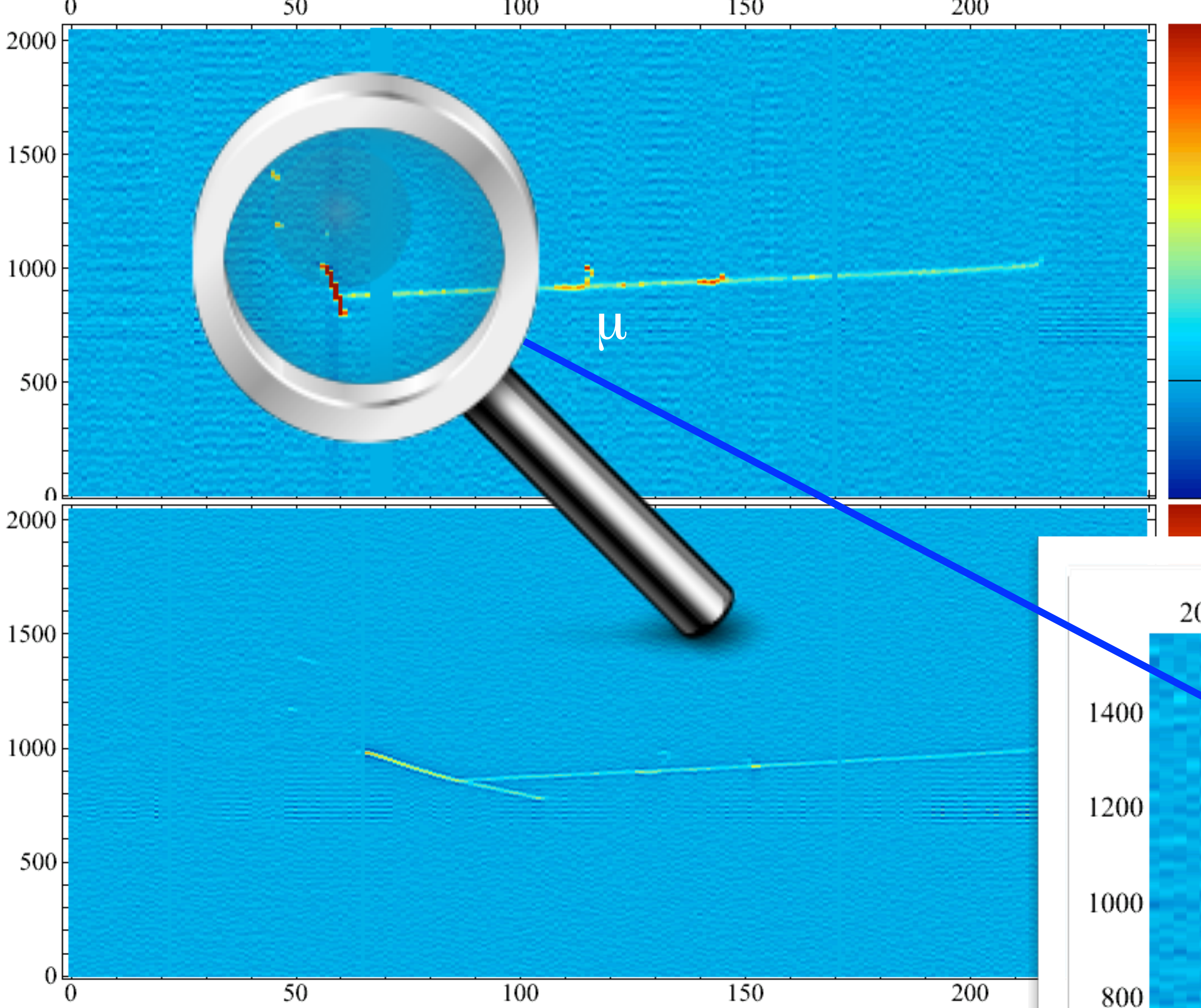
compatible with
1 μ 3p

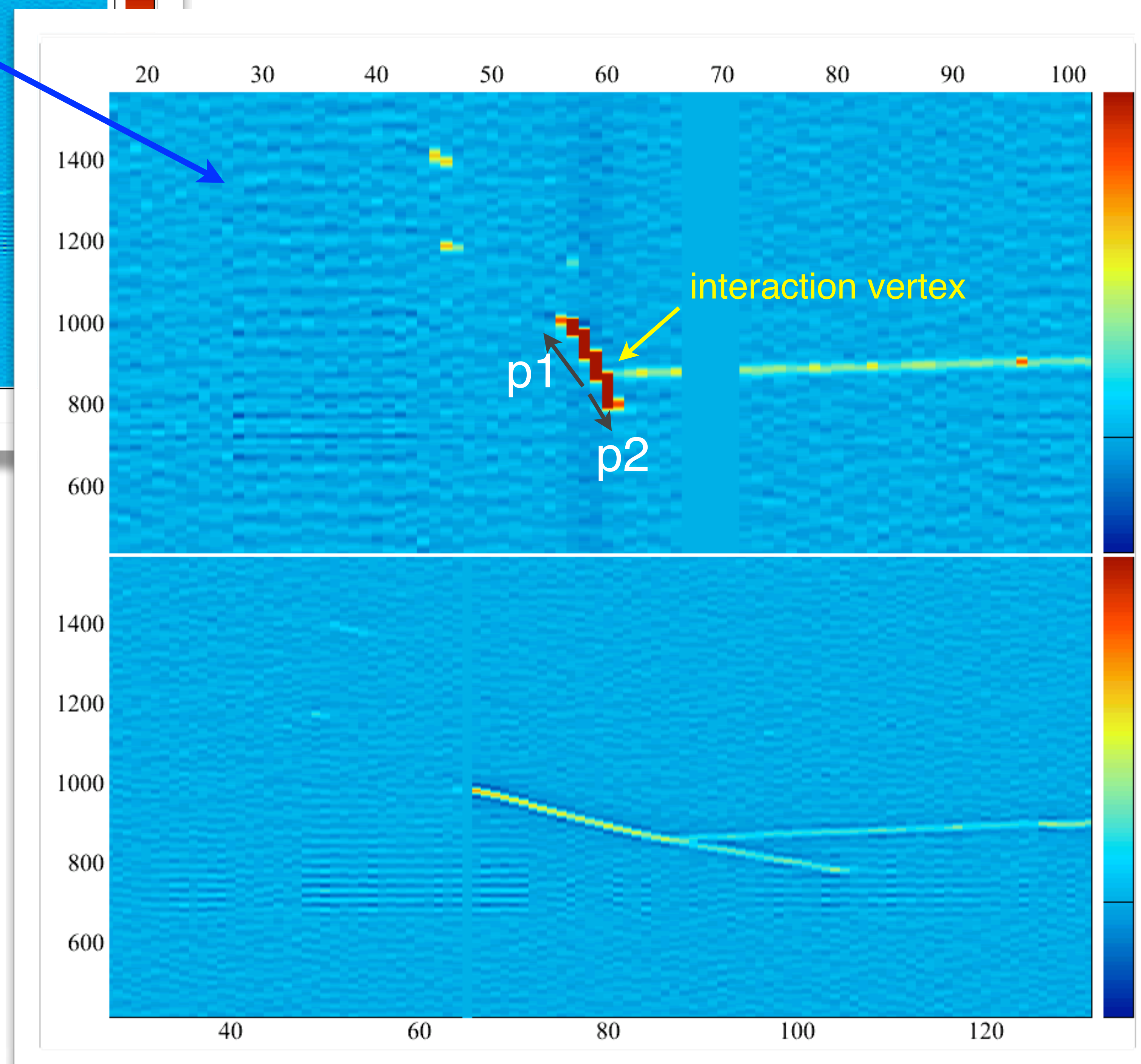
- *p1*: 1.7 cm ----> T=42±4 MeV
- *p2*: 3.6 cm ----> T=64±5 MeV
- *p3*: 11.9 cm ----> T=126±7 MeV



DATA: EXCLUSIVE TOPOLOGIES

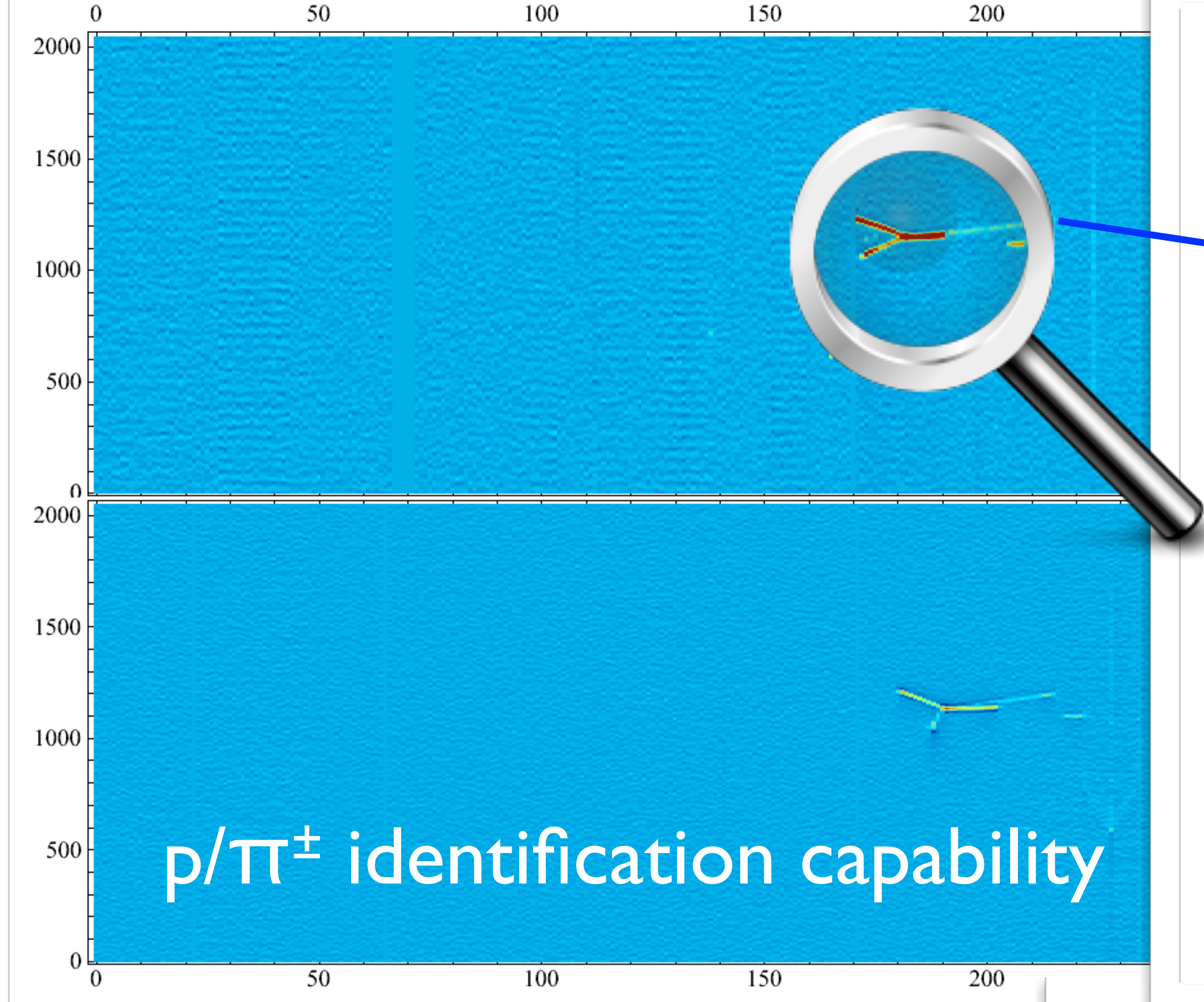
DATA: EXCLUSIVE TOPOLOGIES

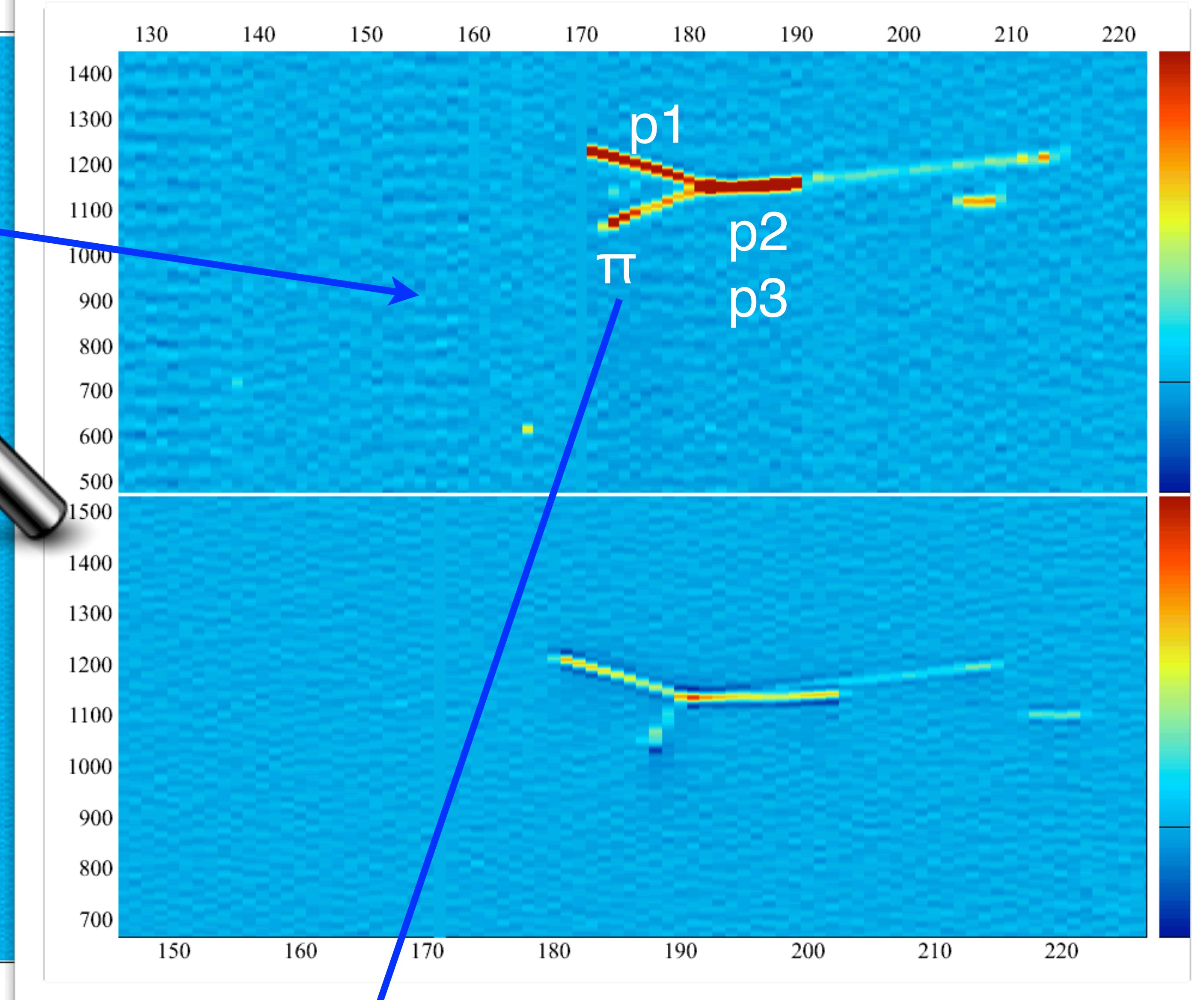


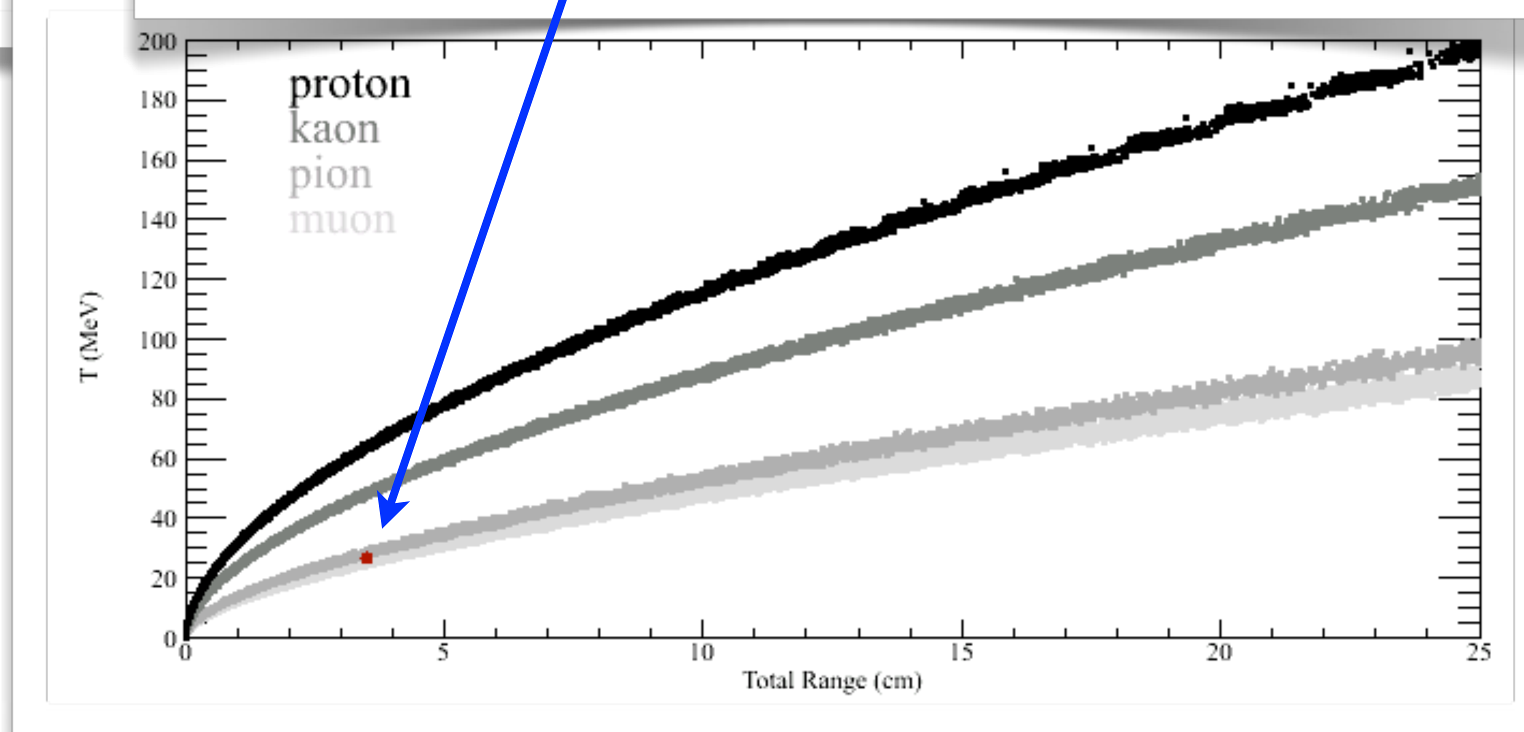


compatible with
1 μ 2p

- *p1*: 8.9 cm ----> T=127±7 MeV
- *p2*: 7.5 cm ----> T=80±5 MeV







- *p1*: 4.9 cm ----> T=83±5 MeV
- *p2*: 5 cm ----> T=134±7 MeV
- *p3*: 5 cm ----> T=134±7 MeV
- π: 3.5 cm ----> T=26±3 MeV

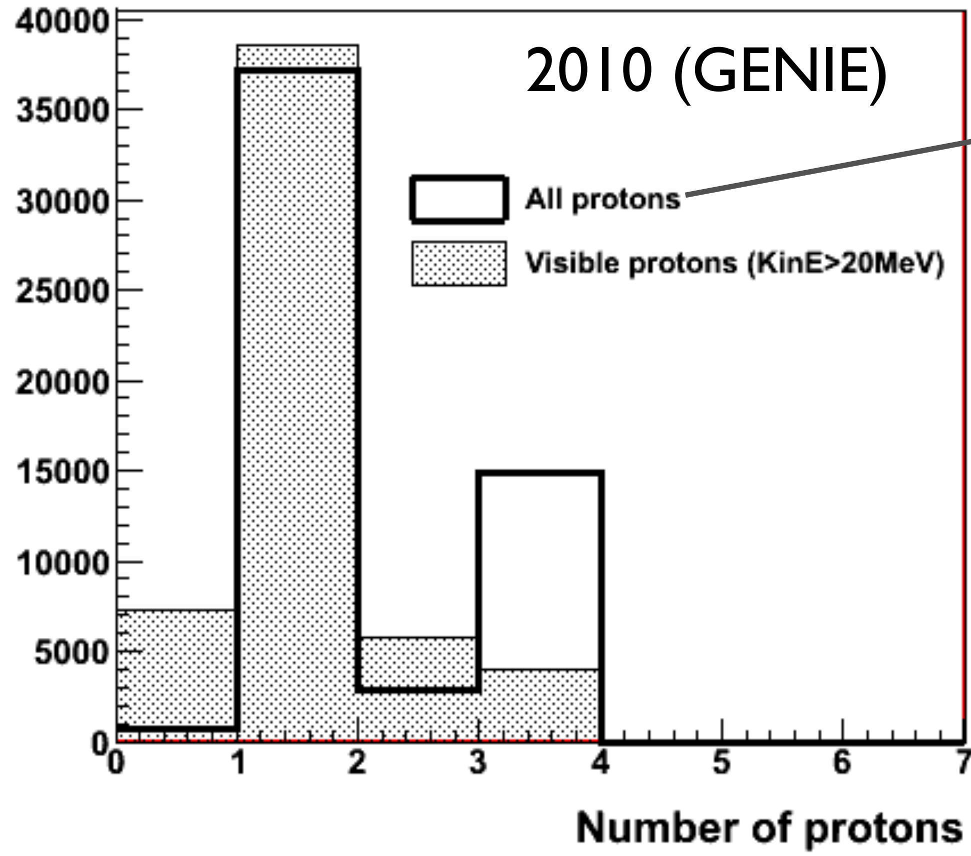
compatible with

1 μ 3p 1 π

Event not in the muon+Np sample

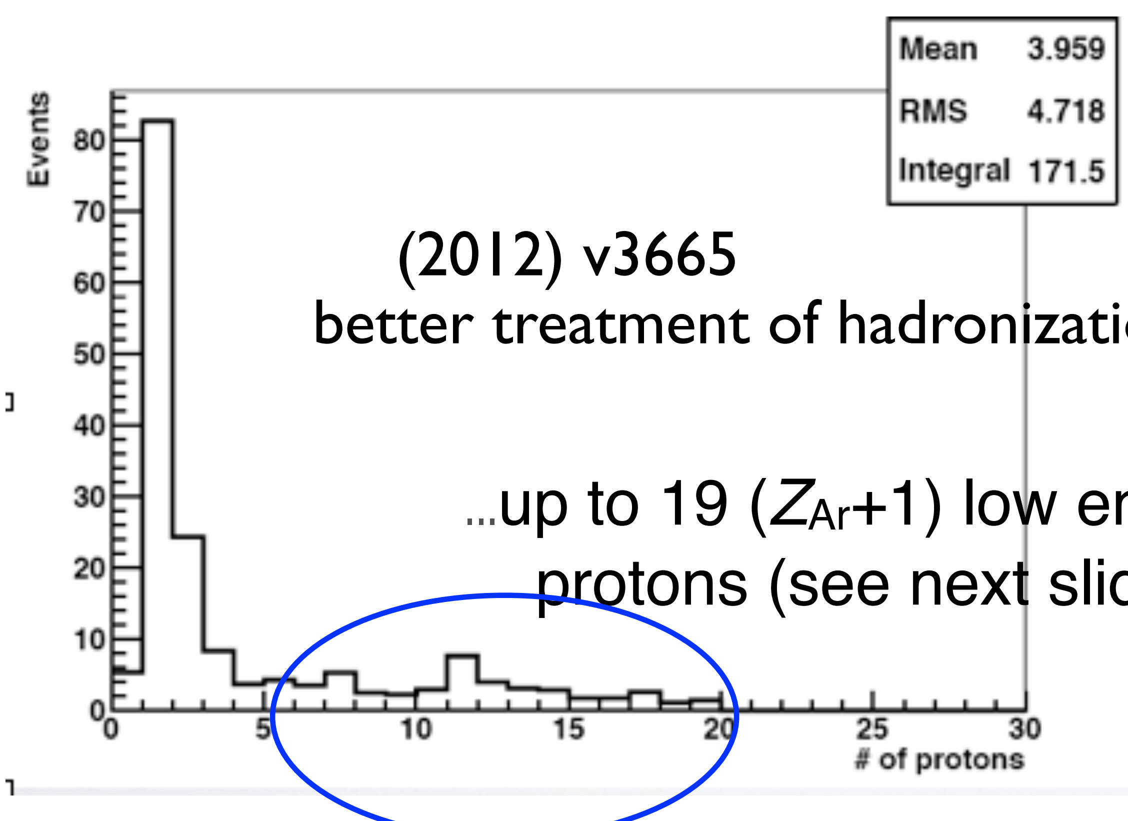
46

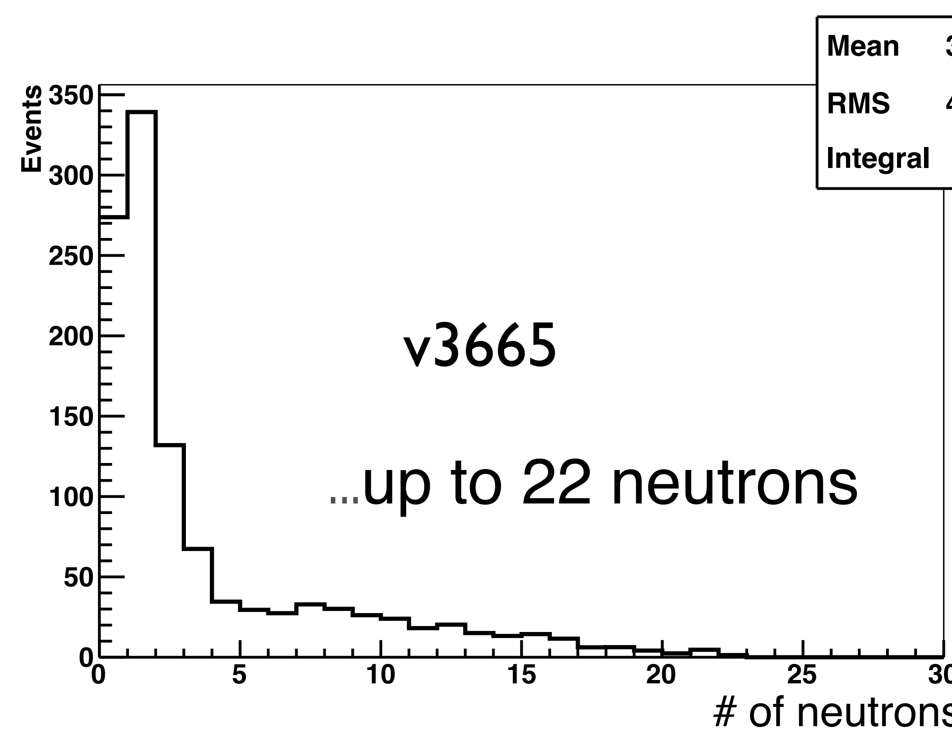
GENIE - NuMI nu mode
Proton multiplicity in μ-Np events in LAr



0p	2%
1p	69%
2p	1%
3p	28%

NuMI beam LE spectrum
- neutrino mode -





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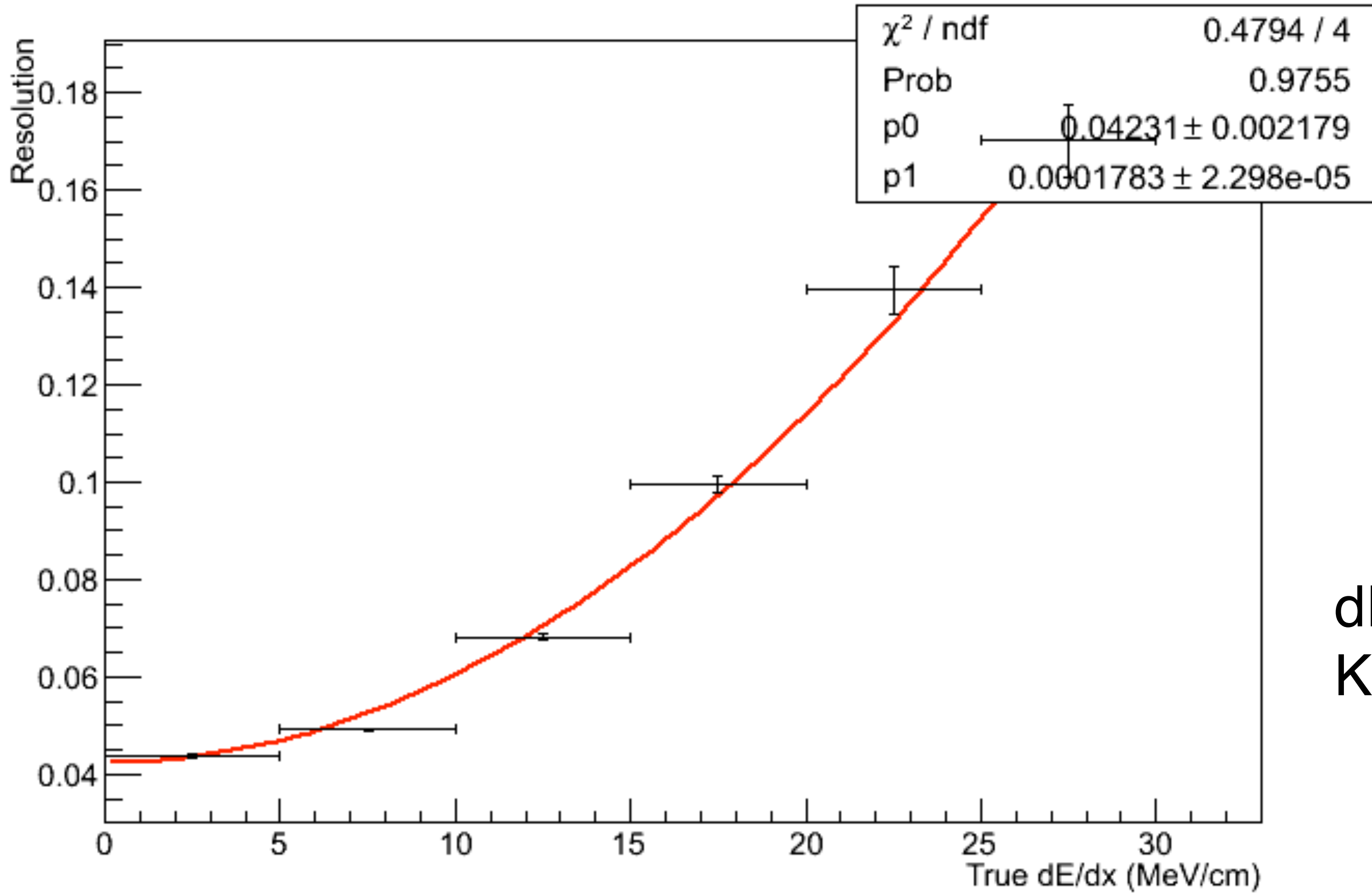
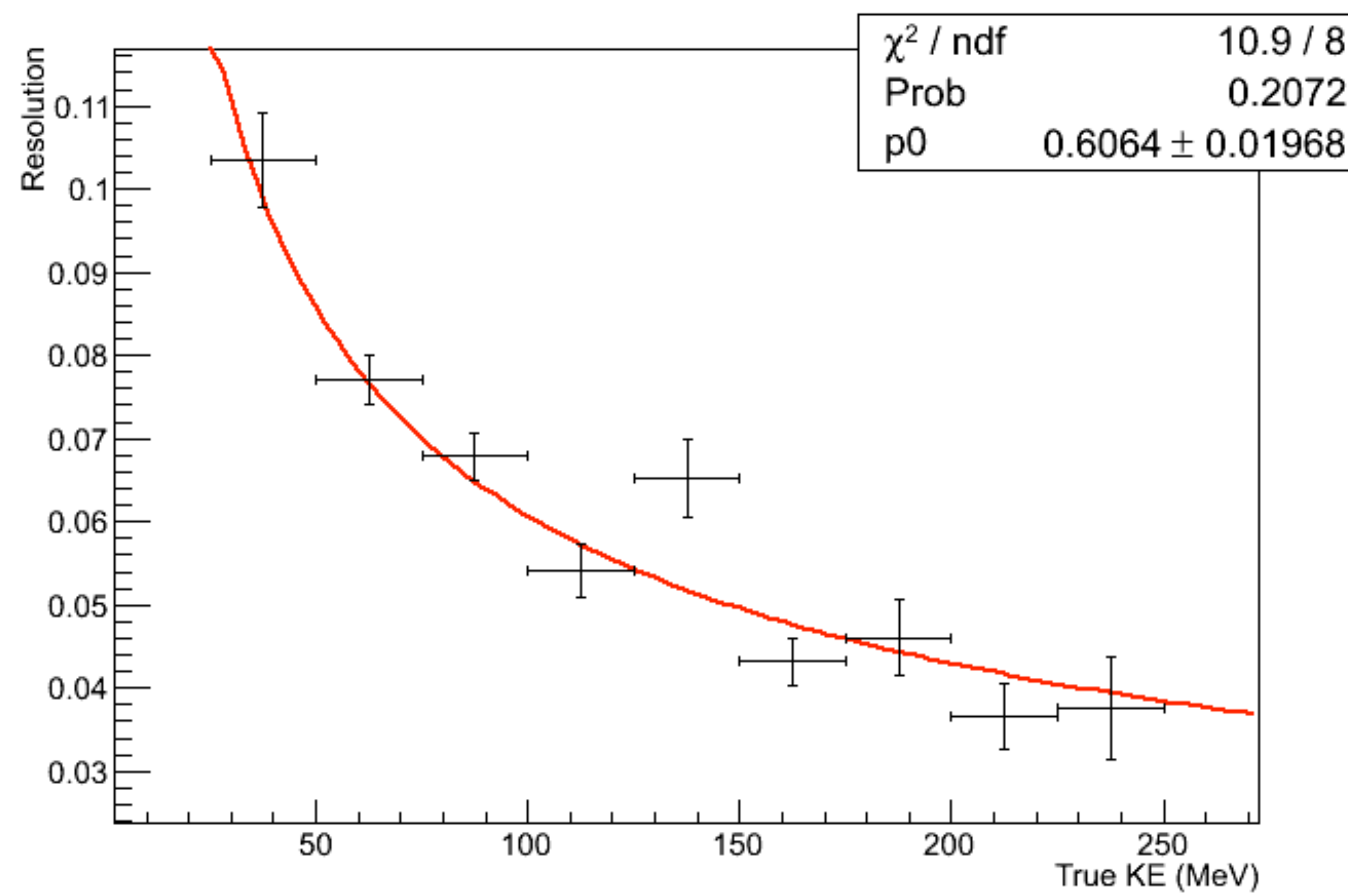


dEdx: 0.04231+0.0001783*(dEdx)^2
KE: 0.6064/sqrt(KE)

ArgoNeuT (4 mm wire pitch) Resolution in dE/dx and Kinetic Energy



Flux for nu-mode

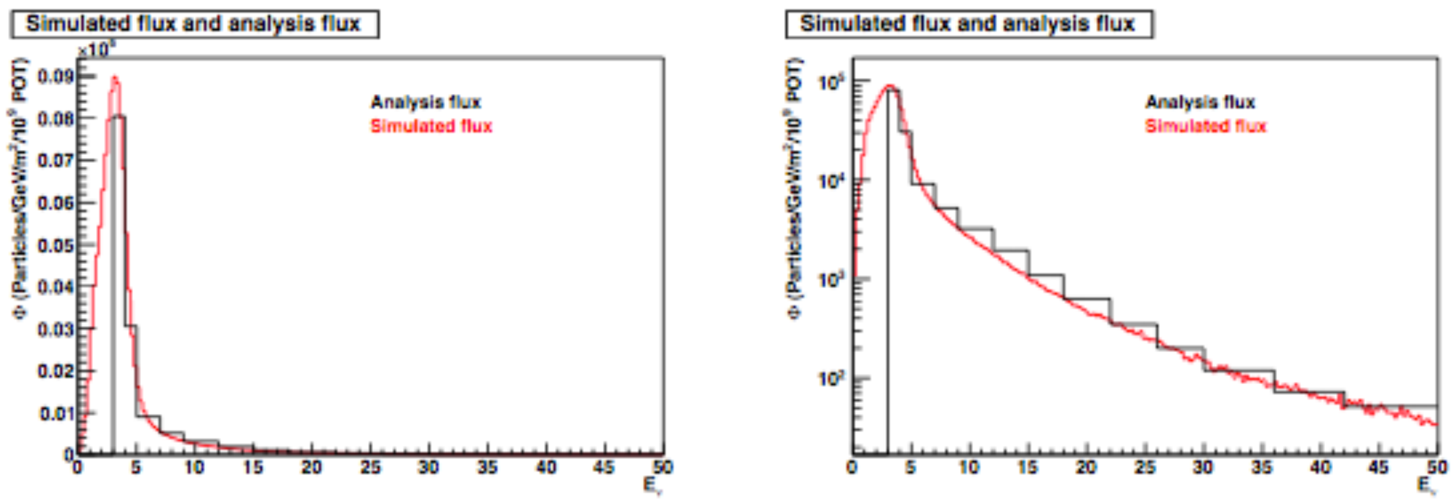
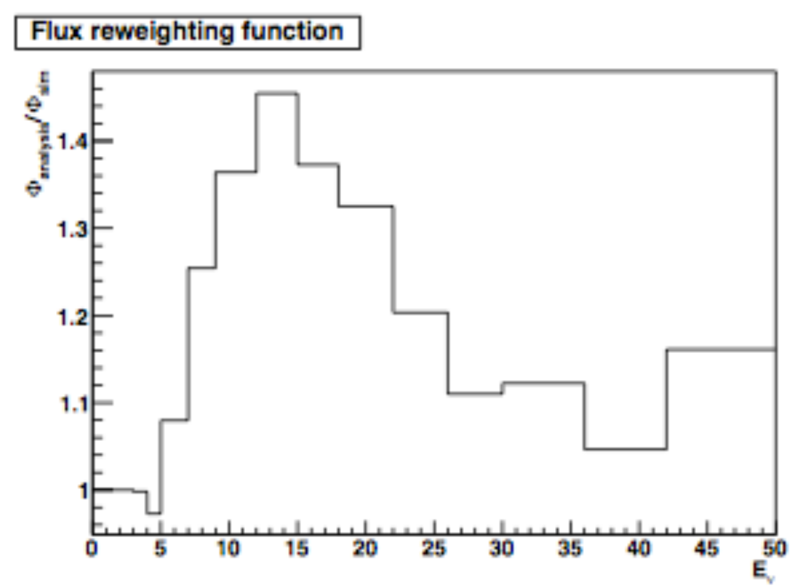


Figure 8.5: The flux employed in the simulation and the flux employed in the analysis with a linear (left) and log (right) y-axis scale. The simulation and analysis fluxes are the same from 0-3 GeV.

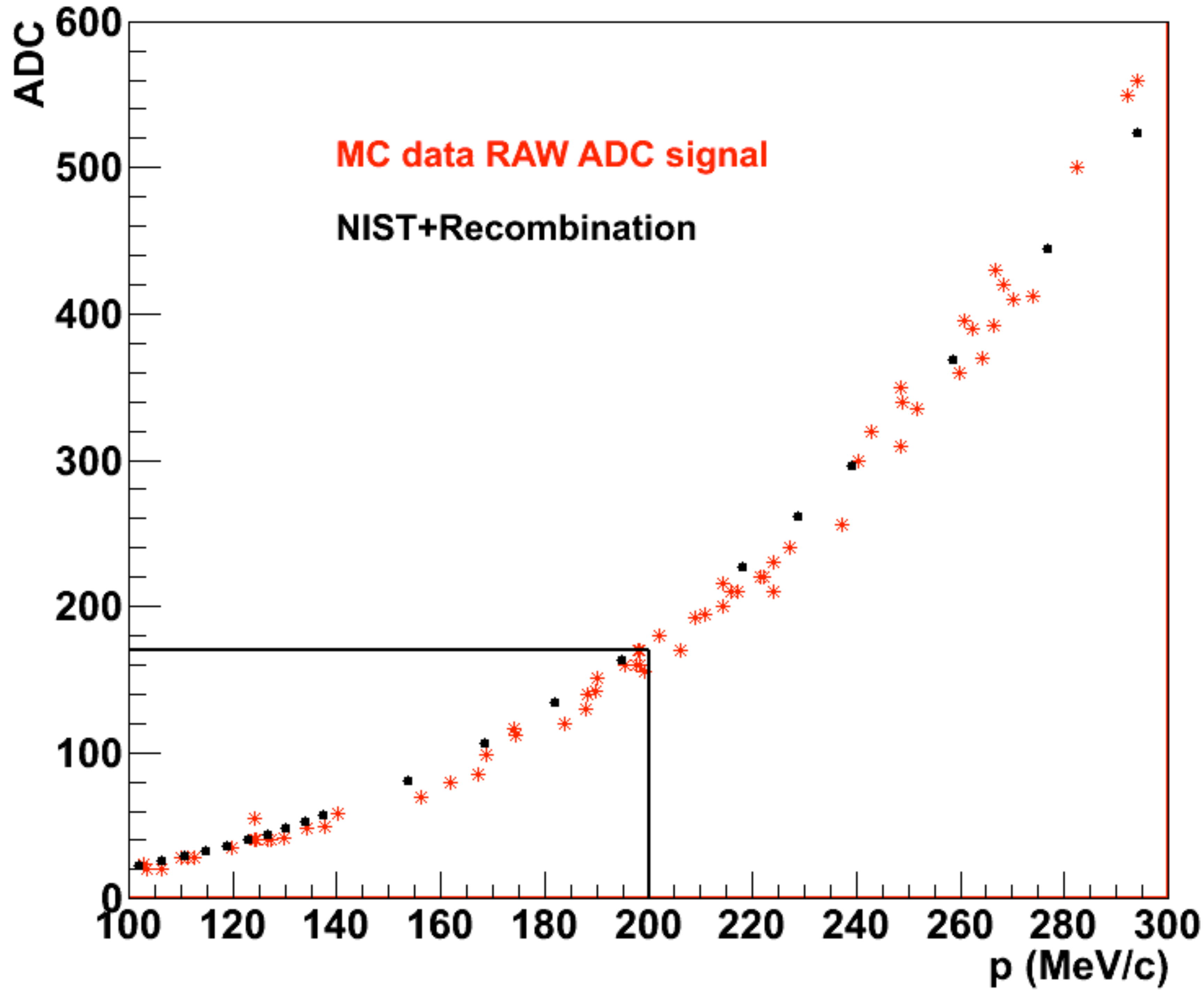


The flux re-weighting function, or analysis flux divided by simulated flux.

from J.Spitz's thesis

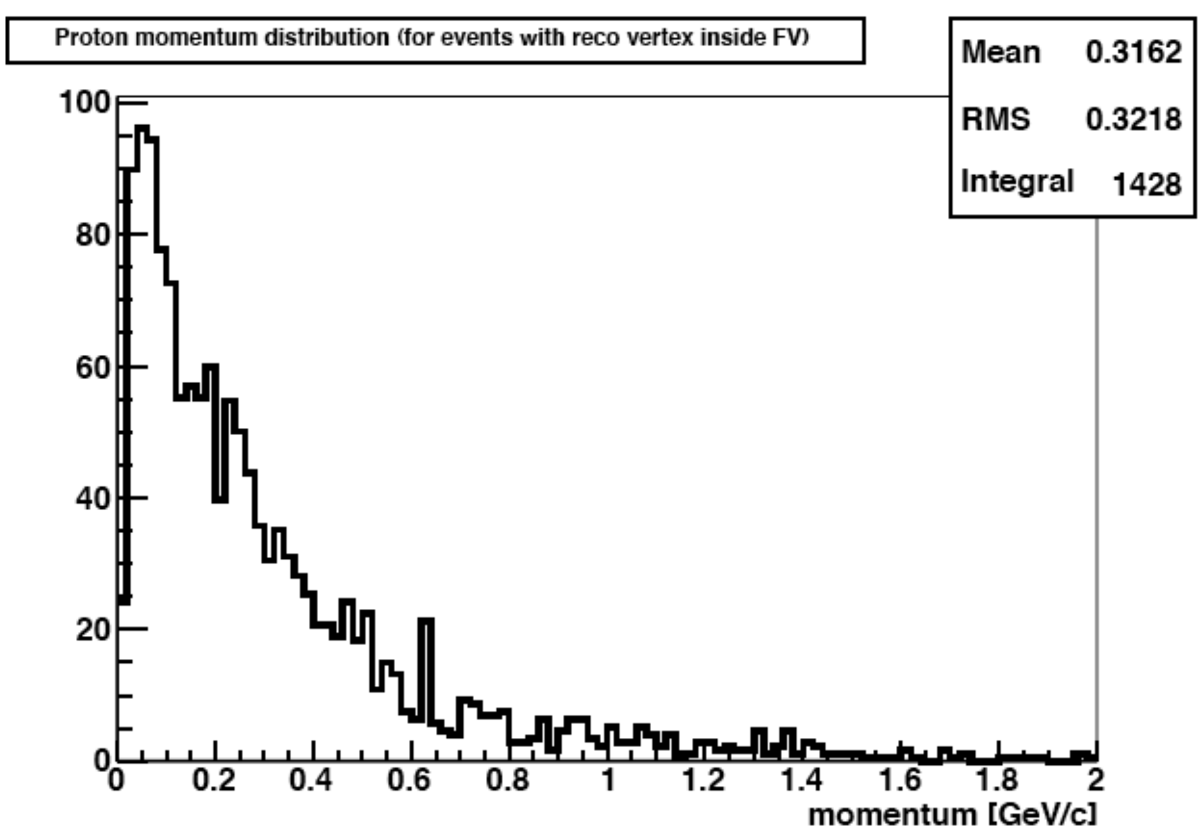
Proton threshold

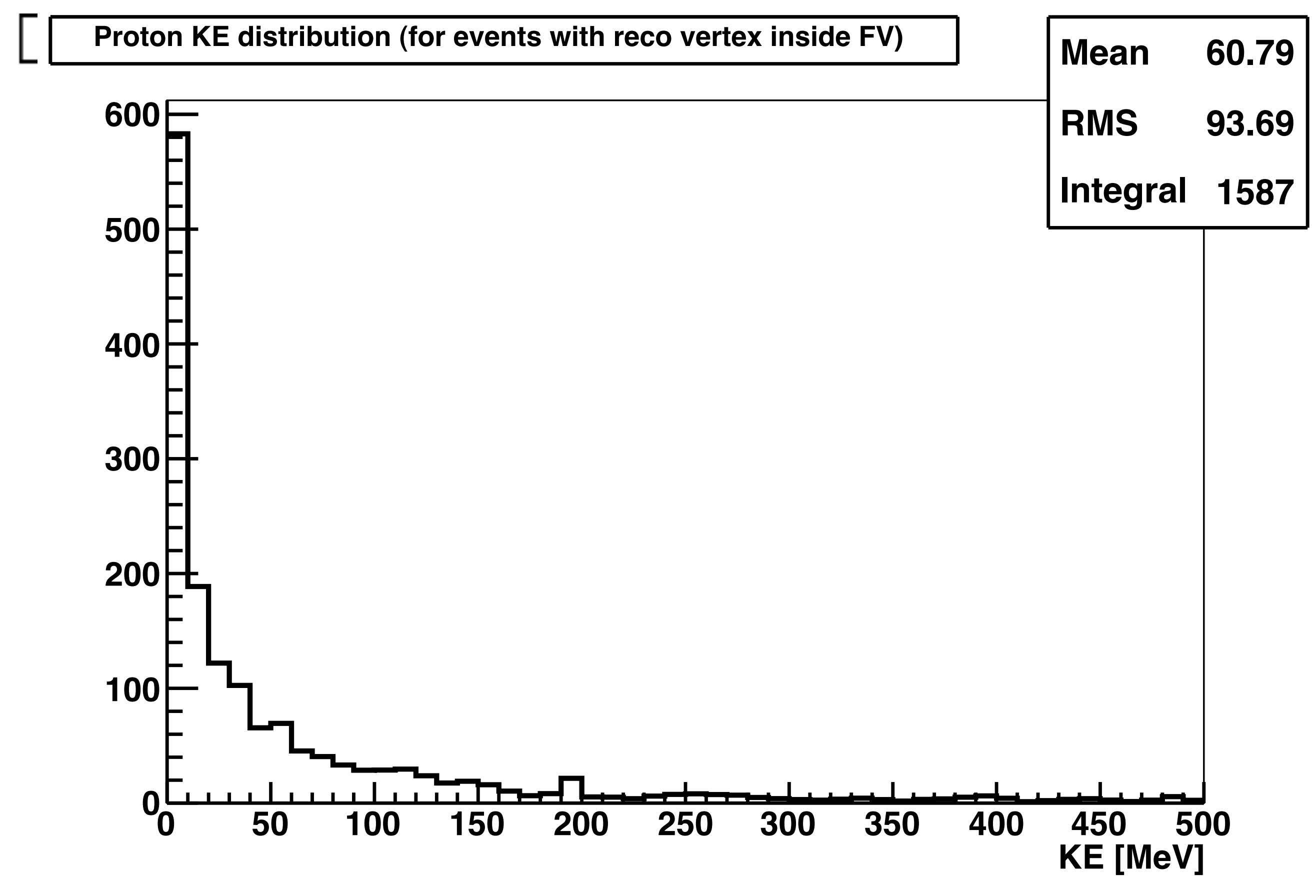
170 ADC --->
p_p=200 MeV/cm
(T_p=21 MeV)



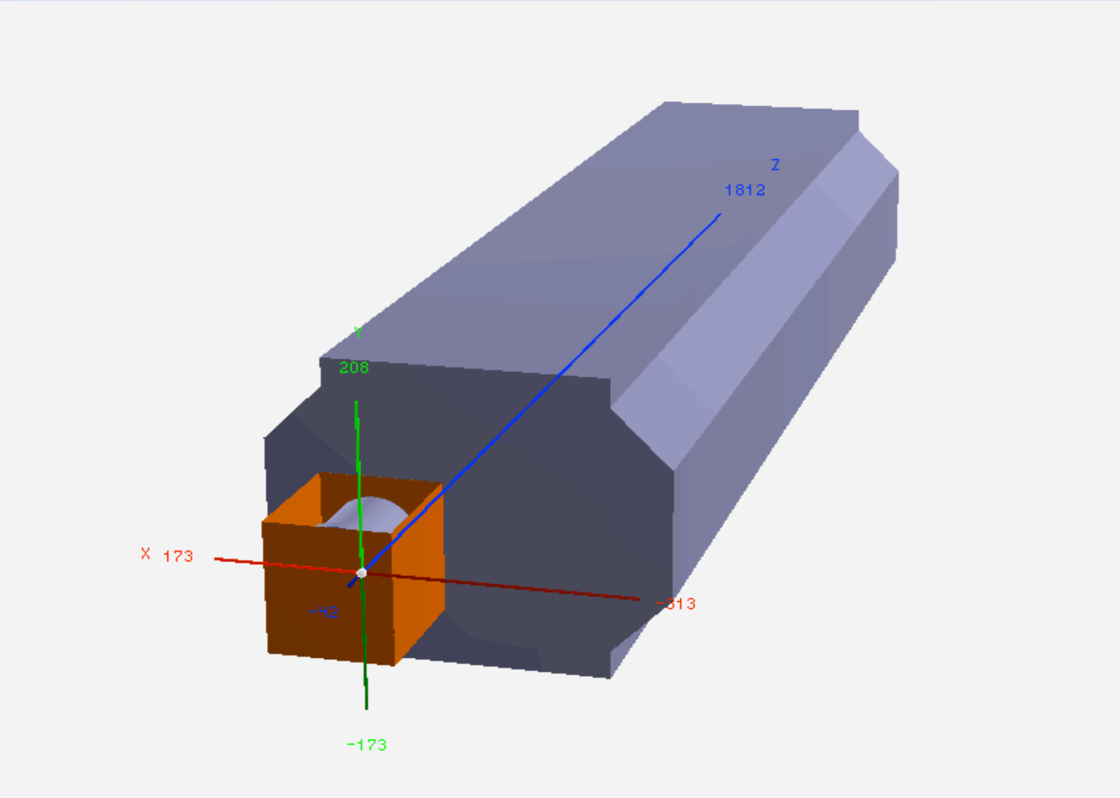
Genie - NuMI nu mode
Proton momentum/Kinetic energy
$\mu^- \ \mathrm{np}$ events

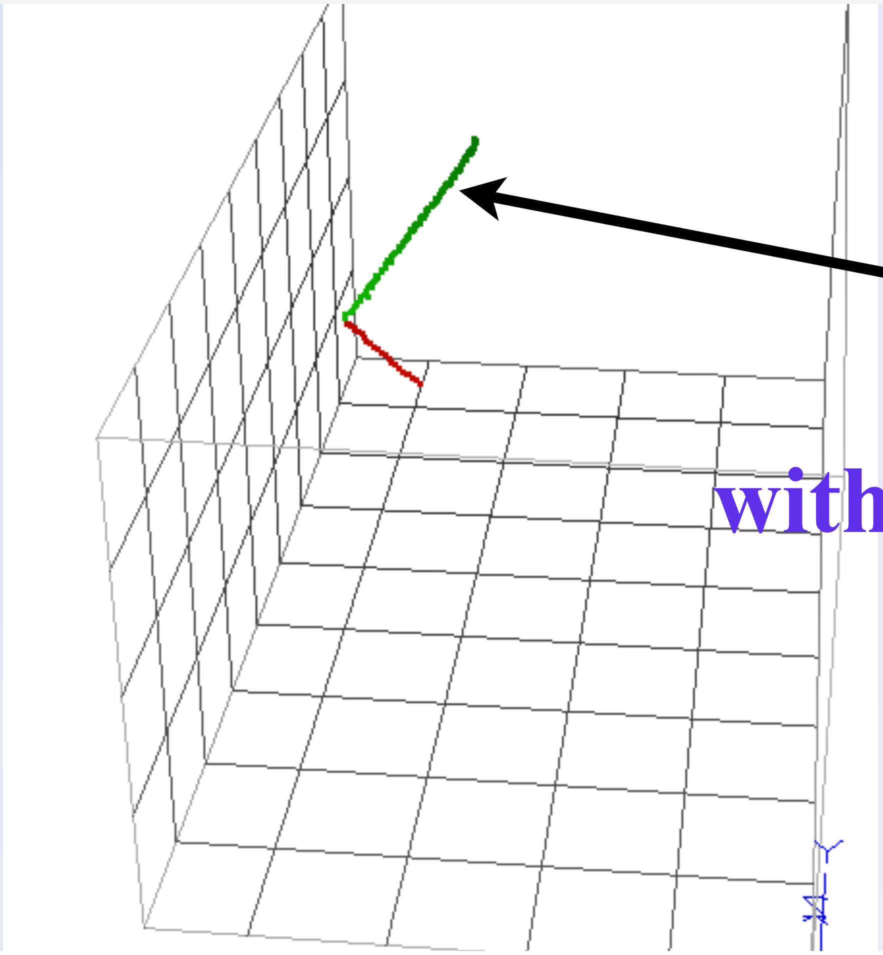
2012 (GENIE in LArSoft)

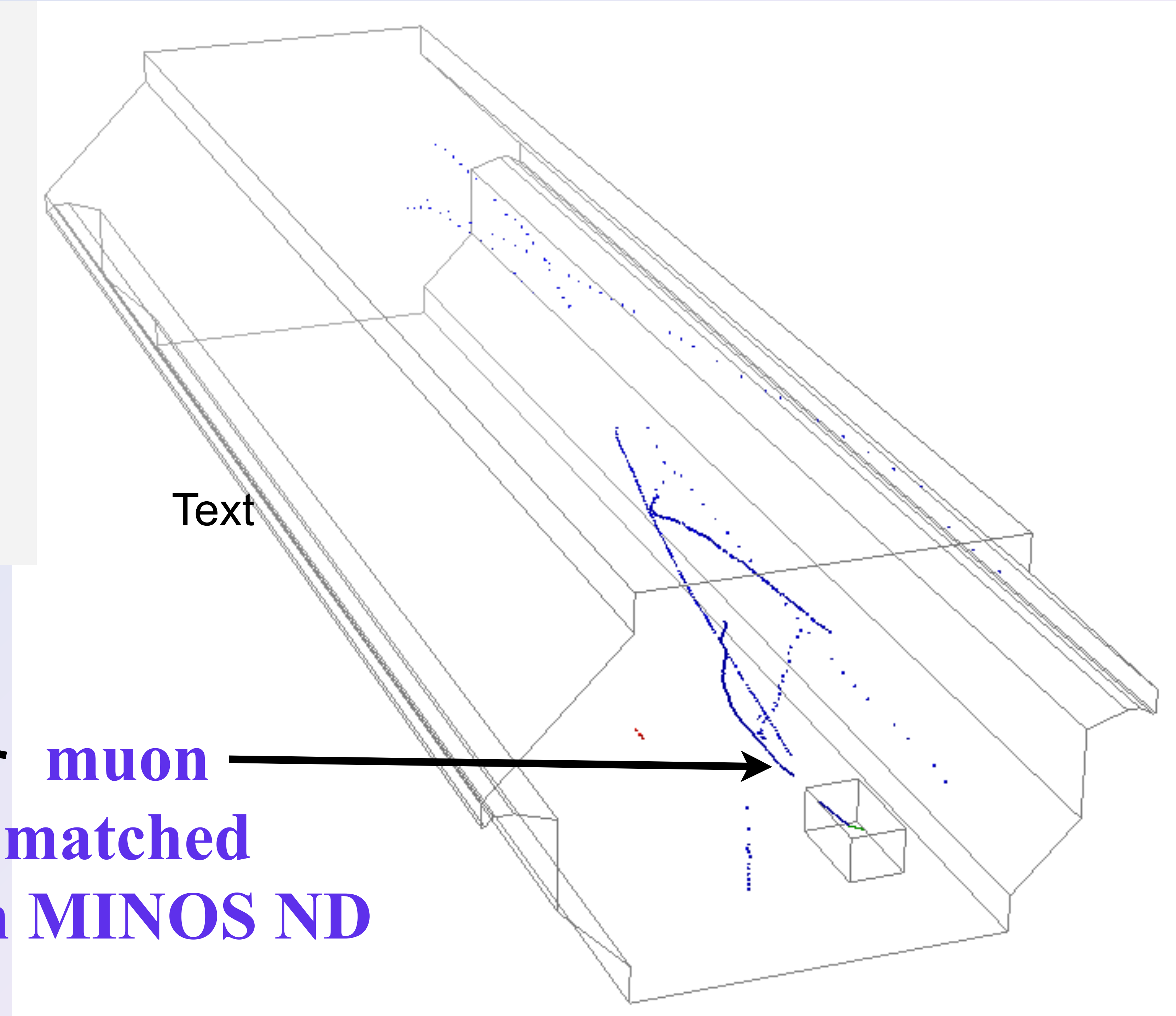




MINOS matching







muon matched with MINOS ND

Calorimetry Example